ACOUSTICAL LETTER

Development of high-sound-insulation double-floor system with Helmholtz resonators: Real-scale experiments with light-steel square pipes

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1. Introduction

In response to the recent environmental issues, the improvement and reuse of existing buildings has become a major subject. The fact that a considerable number of apartment buildings constructed during the 1960's and 1970's seek to be reused, creates the need for renovation and modernization that conform more closely to current acoustic standards. In most cases, increasing the slab thickness is not the best solution because it leads to, for example, excess weight so that high-performance solutions for double floors are required.

Recently, the authors have developed a new type of high-performance double floor with Helmholtz resonators. Good results for heavy-weight impact sound insulation were obtained in an experiment [1]. Furthermore, theoretical analysis based on a two-particle model was developed to clarify the effects of the specifications of the double floor [2]. Although the new double floor performed satisfactory regarding heavy-weight impact sound insulation, high construction costs made it impractical. For this reason, with the primary objective of reducing the construction cost, materials such as cardboard, gypsum boards and expanded polystyrene boards have been tested for fabricating Helmholtz resonators [3]. In addition, light-steel square pipes (hereafter called "square bars") were also used, and promising results were obtained in an experiment with single unit models [4]. On the other hand, it is of great importance to verify the validity of the unit experiments by full-scale tests.

We present the experimental results for full-scale samples ($2.7 \times 3.6\,\mathrm{m}^2$) of high-sound-insulation double-floor systems with Helmholtz resonators made of square bars. Impact tests were carried out in a real-size laboratory building, and the slab thickness was 180 mm (see Fig. 1).

2. Floor impact sound measurements

2.1. Double-floor characteristics

Sample structures consisting of a double-floor system (see Fig. 2) were formed with a hard flooring layer (12 mm), particle board (20 mm) and square bars ($45 \times 100\,\mathrm{mm}^2$, thickness: 0.45 mm), all supported by steel angles and rubber vibration isolators ($35 \times 35 \times 25\,\mathrm{mm}^3$). The necks of resonators, made of PVC pipes (thickness: 2.5 mm), were located along the length of square bars. Both vertical and horizontal positions of square bars were chosen in order to compare the effects produced by the resonators on the floor insulation performance. The cross-sectional second moments of horizontal (I_{xx}) and vertical (I_{yy}) positions can be seen in Fig. 3.

2.2. Test description

A total of four kinds of double-floor samples with Helmholtz resonators having different characteristics were tested. Schematic drawings of the four full-scale samples and their specifications are shown in Fig. 4 and Table 1, respectively. For Samples 1 and 2, the lengths of square bars were equal to the specimen width, while for Samples 3 and 4, steel angles were placed in the middle of the test pieces to elucidate how rigid elements affect the double-floor efficiency, as can be observed in real situations. The calculation of the natural frequency f_0 ($\approx 10\,\mathrm{Hz}$ to $15\,\mathrm{Hz}$) for choosing the size ($35 \times 35 \times 25\,\mathrm{mm}^3$) and hardness ($40°$) of rubber vibration isolators (static spring constant $1.01 \times 10^5\,\mathrm{N/m}$, dynamic spring constant $1.29 \times 10^5\,\mathrm{N/m}$) was based solely on the performance of a rubber spring (not air spring). The resonance frequencies, f_{low} and f_{high}, obtained using the two-particle model [2] are also shown in Table 1.

The excitation points and microphone points (0.6, 0.8, 1.0, 1.2, and 1.4 m height) are shown in Fig. 5. Measurement was performed not only in 1/1 octave bands but also in 1/3 octave bands, identified using Japanese Industrial Standard (JIS 1418-2:2000); a tire machine and rubber ball were used as the standard heavy-weight floor-impact sources. Figure 6 shows pictures taken during the fabrication of specimens and during impact sound tests.

3. Results

3.1. Floor-impact sound-pressure level

The results of the floor-impact sound-pressure levels for

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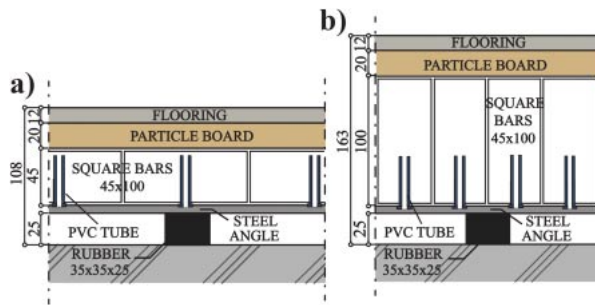**Fig. 1** Acoustic laboratory building.

Fig. 2 Double floor with Helmholtz resonators: a) horizontal position of square bars, and b) vertical position of square bars. Distances in mm.
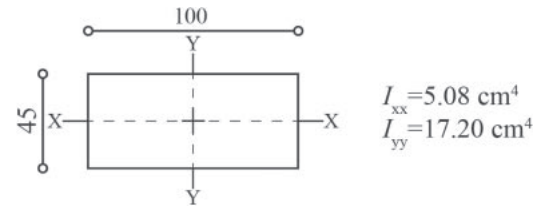

Fig. 3 Cross-sectional second moments of square bars.

the different impact sources can be seen in Fig. 7. Graphs show a clear difference between the results for heavy-weight and light-weight impact sources. In the case of the tire machine test, Samples 1 and 3 seem to have the same effect as a bare slab for frequencies under 250 Hz. Although something similar occurs in rubber ball source experiments for Samples 1 and 3, the difference between double-floor tests for Samples 2 and 4 and bare slab tests is more significant. Results of the tapping machine test show clearly how the 250 Hz band determined the L-value (L_r) for every single test. Furthermore, even if the flooring is a hard type, the L-number (L_n) for Samples 1 and 4 was 48 (see Table 2), very close to the value of 45 required for the 1st class housing slabs by the Architectural Institute of Japan (AIJ).

3.2. Reduction of floor-impact sound-pressure level

The reduction of floor-impact sound-pressure level ΔL_n ($\Delta L_n = L_n$ (slab) $- L_n$ (sample)) for the four double-floor tests is shown in Fig. 8. From the results, it can be seen that,
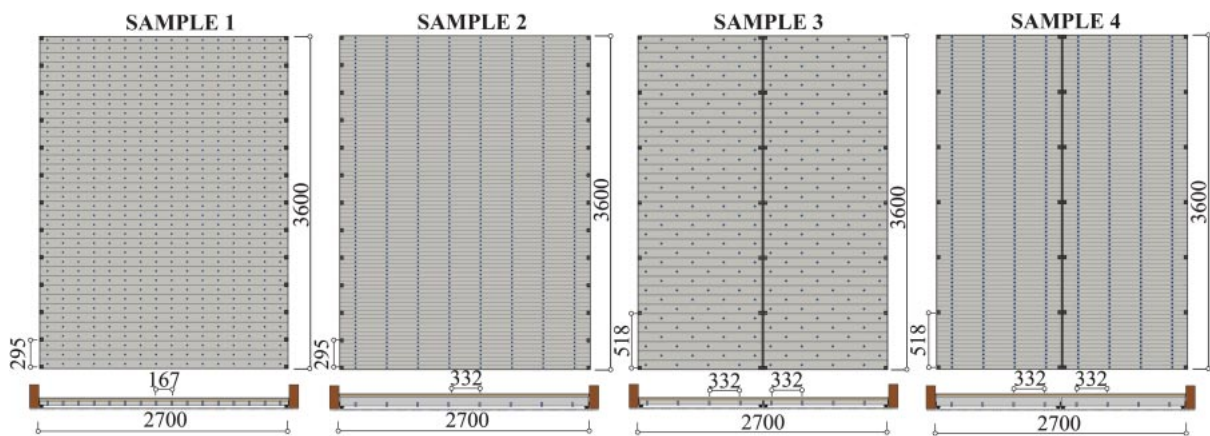

Fig. 4 Double floor with Helmholtz resonators: full-scale samples. Distances in mm.

Table 1 Double floor with Helmholtz resonators: specifications of full-scale samples.

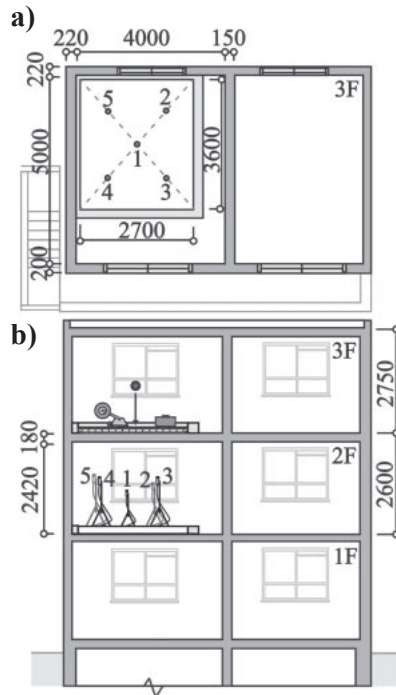|	Square bar	Span (m)	Resonator tube size (mm)	Resonator tube spacing, volume	Floor thickness (mm)	No. of rubbers	Rubber support load (kg)	f_0 (Hz)	f_{low} (Hz)	f_{high} (Hz)	Total load, load/m²
SAMPLE 1	Horiz.	2.7	13ϕ L = 40	167 mm, 729.8 cm³	108	26	14.1	15.2	36.5	166.8	365.3 kg, 37.6 kg/m²
SAMPLE 2	Vert.	2.7	13ϕ L = 40	332 mm, 1,451 cm³	163	26	19.5	12.9	24	153.6	506.5 kg, 52.1 kg/m²
SAMPLE 3	Horiz.	1.35	13ϕ L = 40	332 mm, 1,451 cm³	108	28	14.2	15.2	34.5	121.7	397.2 kg, 40.9 kg/m²
SAMPLE 4	Vert.	1.35	13ϕ L = 40	332 mm, 1,451 cm³	163	28	19.2	13	20.8	153.4	538.4 kg, 55.4 kg/m²

Fig. 5 Full-scale laboratory views: a) plan and b) section. Distances in mm.

Fig. 6 Left: Placement of square bars in double floor; Right: Tire machine test.

in general, there is a great increase in ΔL_n, the most significant improvement being observed in the tapping machine tests. In Samples 3 and 4, an improvement in ΔL_n

Table 2 L-number (L_n), L-value (L_r), and ΔL_n.

SAMPLE	Tire mach.			Rubber ball			Tapping mach.		
	L_n	L_r	ΔL_n	L_n	L_r	ΔL_n	L_n	L_r	ΔL_n
SLAB	58	60	0	55	55	0	76	75	0
1	58	60	0	49	50	6	48	50	28
2	52	50	6	44	45	11	51	50	25
3	55	55	3	47	50	8	49	50	27
4	53	55	5	42	40	13	48	50	28

for the three impact sources can be observed for 63 Hz compared with Samples 1 and 2, respectively. The reason is the placement of the angle in the middle of Samples 3 and 4, which may have given more rigidity to the test pieces. Moreover, the results for the tire machine source in Sample 4 particularly improved from 63 Hz to 100 Hz in comparison with Sample 2, and were similar to the results for the rubber ball source test in this frequency range. Furthermore, it can be seen clearly how Samples 2 and 4 show a great increase in ΔL_n for frequencies between 50 Hz and 150 Hz compared with Samples 1 and 3.

3.3. Comparison with theoretical and unit-model experimental results

To gain a better understanding of the results shown, it is of great importance to compare them with the theoretical and unit-model ($300 \times 300 \, \text{mm}^2$) experimental results.

The comparison of the theoretical results between the horizontal and vertical placements of square bars is described in Ref. [4]. Figure 9 shows the vibration transmissibility (τ) from the theoretical and unit-model experimental results (taken from Figs. 15 and 16 in Ref. [4]. They correspond to the results for Samples 3 and 4 in this paper). Specifications can be found in Fig. 1 of Ref. [4], however, there are slight differences from Samples 1 to 4 of present report. Theoretical results show two resonance peaks due to the Helmholtz resonators for the horizontal position ($f_{\text{low}} = 50.9$ Hz, $f_{\text{high}} = 117.4$ Hz) and the vertical position ($f_{\text{low}} = 37.7$ Hz, $f_{\text{high}} = 142.5$ Hz) of square bars. At the first instance, both sets of results seem to be very favourable because of the appearance of antiresonance dips. However, the unit-model experimental
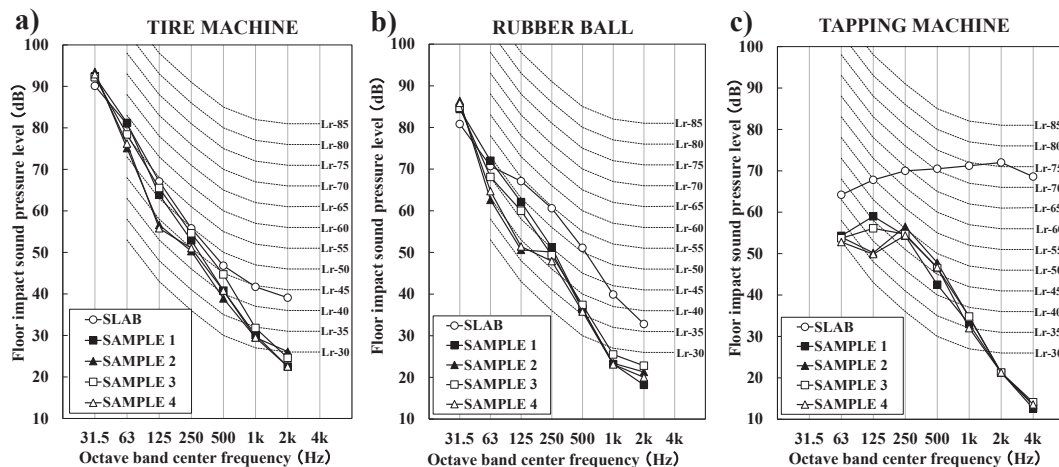

Fig. 7 Floor-impact sound insulation: a) tire machine, b) rubber ball, and c) tapping machine.
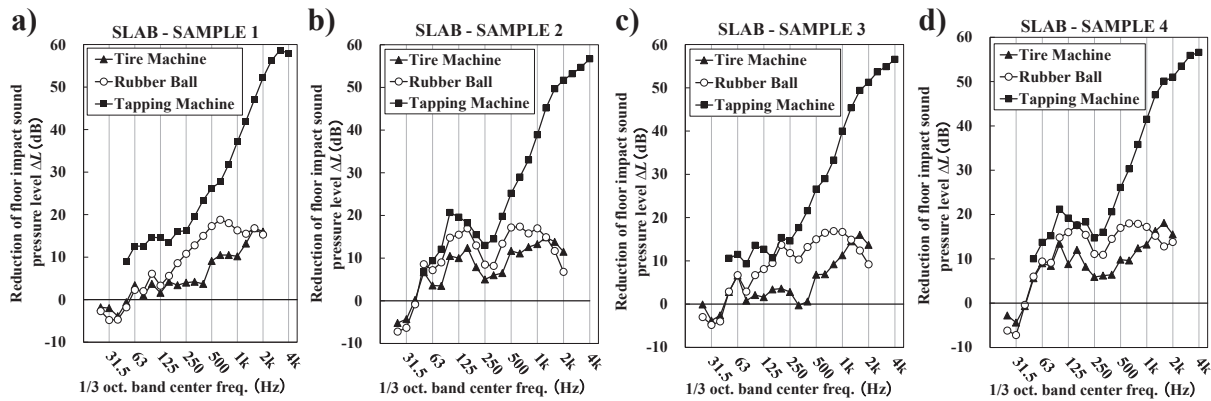
Fig. 8 Reduction of floor-impact sound-pressure level ΔL: a) Sample 1, b) Sample 2, c) Sample 3, and d) Sample 4.
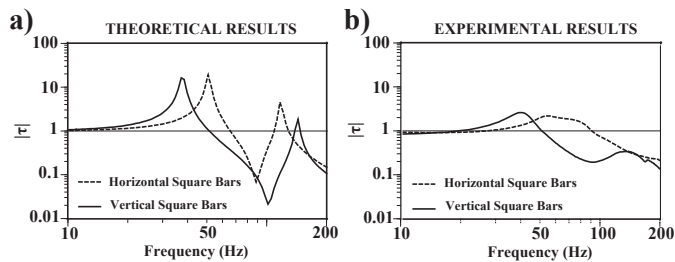

Fig. 9 a) Theoretical calculation results and b) unit-model experimental results [4].

results show that the horizontal position in the square bars model has no dip. This can be caused by the low rigidity in the lower surface of square bars [4], and various kinds of damping, the influence of which is apparent especially when the resonance frequencies are close to each other. On the other hand, results for the vertical position of square bars in the experimental model show an appropriate and promising performance of Helmholtz resonators, giving a better explanation of the good results obtained for Samples 2 and 4.

4. Conclusions

This research has shown the effectiveness of a double-floor system with Helmholtz resonators for floor-impact sound. A general reduction in the floor-impact sound-pressure level ΔL was obtained from all impact sound sources. The reduction was more significant for tapping machine tests; even with the hard-type floor, the L-number in all samples was very close to the value of 45 required for light-weight impact tests by the AIJ. On the other hand, the existence of the angles in the middle of Samples 3 and 4 leads to an improvement in ΔL for 63 Hz for all impact sources. Also, the results for Sample 4 in a tire machine test are better in 1/3 octave bands, which is similar to the rubber ball test results from 63 Hz to 100 Hz. Good results were obtained for Samples 2 and 4 owing to the effective performance of Helmholtz resonators with the vertical position of square bars.

The ideal double-floor height should be reduced. For this reason, future works will also focus on reducing the height of the double-floor system while maintaining the effectiveness of the Helmholtz resonators.

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Antonio Sanchez-Parejo received his Master of Engineering in Acoustics at the University of Granada, Spain, in 2013. In 2011 he was awarded the Initiation to the Investigation scholarship in the interdisciplinary (Architecture, Structures, Seismology and Physics) research group SNADS (Signal and Numerical Analysis in Dynamical Systems) at the University of Granada. His studies and research were enriched with stays at Tongji University, Shanghai, China in 2012 and Tokyo Institute of Technology, Japan in 2013. Since 2014 he has worked in Japan for the architectural and acoustic design company YAB Corporation, where his research interests include room acoustics, vibration, noise control and Japanese kabuki playhouses among others.