REDUCTION OF STRUCTURE-BORNE SOUND USING TUNED MASS DAMPERS COMPRISED OF GRANULAR MATERIALS

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Reducing structure-borne sound in concrete buildings is difficult, because concrete has low internal damping. We tried to reduce concrete slab vibrations in their lower frequencies using granular materials. The granular materials are retained in polyethylene bags, which are placed in the cavities of voided concrete slabs. They act as Tuned Mass Dampers (TMDs), with the bags working as springs, and the granular materials as masses. Lower frequency vibrations in concrete slabs are reduced by the granular materials in the bags. As a result, structure-borne sound, such as floor impact sound, is reduced. In this study, laboratory experiments were conducted into reducing the vibration of a concrete slab. The vibration characteristics of a voided slab both with and without granular materials in the cavities were compared. Vibrations were significantly reduced across a specific range of frequencies. The frequency range shifted as the mass of granular materials or thickness of the polyethylene bags changed. As a result, it was presumed that vibrations were reduced by a TMD mechanism. Numerical analysis was also conducted using the Finite Element Method. The vibration characteristics of a slab model with and without TMDs were calculated. The results from the calculations and experiments demonstrated good agreement. It is concluded that granular materials in polyethylene bags act as TMDs and reduce vibrations in concrete slabs.

Keywords: structure-borne sound, granular materials, tuned mass damper, floor impact sound, reduction

1. Introduction

Airborne sound is relatively easily suppressed, however structure-borne sound is hard to reduce in concrete buildings because concrete has very low internal damping, and vibrations are hardly attenuated if an impact is applied. If the internal damping of concrete can be increased, structure-borne sound should be reduced.

Reference [1] shows an example of a concrete block wall. Large vibration attenuation is obtained in relatively high frequencies by plugging the cavities of the concrete block wall with sand.

However, problems with structure-borne sound, such as heavy floor-impact sound or sounds excited by train traffic, occur at low frequencies, especially in the 63-Hz octave band. Therefore we tried to apply high damping performance to concrete slabs at low frequencies. Voided concrete slabs are used as concrete floors and granular materials retained in bags are installed in the cavities. The granular materials and bags reduce the vibrations of these concrete slabs. The vibration characteristics of the concrete slabs are re-attuned to those of high-damping concrete slabs.
2. Voided concrete slab with granular materials retained in bags

Figure 1 shows a photograph of the cross section of a voided concrete slab with granular materials. The cavities are formed using pipes, which have an elliptical cross section. The sectional dimensions and the pitch of the cavities were determined as shown in Fig. 2 so that the hollow ratio would be as large as possible. The granular materials are retained in bags and placed in the cavities. The granular materials are sand, which have a particle size of 1.0 to 2.5 mm and a weight per unit volume of 1.6 kg/l. The bags are made of polyethylene film.

Figure 1: Photograph of voided slab with granular materials in the cavities

Figure 2: Cross section of the slab

3. Vibration reduction experiment

Laboratory experiments were conducted into vibration reduction of a voided concrete slab.

3.1 Experimental conditions

A voided slab having a length of 6.0 m and width of 1.2 m was prepared as a test slab. The voided slab was placed on the floor of a laboratory with vibration isolation support as shown in Fig. 3. The resonance frequency for vibration isolation was about 10 Hz, which is sufficiently lower than the frequencies of structure-borne sound.

Six granular material bags were installed per cavity, with a total of 102 bags installed in 17 cavities. As shown in Table 1, four conditions (Case 1 to Case 4) were set with different thicknesses of bags or masses of granular materials. The “thin film” shown in Table 1 is a film with a thickness of 0.13 mm. The “layered film” is five layers of overlapping 0.17-mm thick film. A reference condition without granular materials (Case 0) was also set.

The end of the slab was excited using an impact hammer and vibrations were measured at points aligned along the center of the slab. They are indicated by dots in Fig. 3. Impedance levels were obtained from the excitation force (output from the impact hammer) and the vibration velocity at the measurement points.
### Table 1: Conditions of granular materials

<table>
<thead>
<tr>
<th></th>
<th>Case 0</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of granular materials per bag (102 bags)</td>
<td>none</td>
<td>3.75 kg</td>
<td>3.75 kg</td>
<td>2.50 kg</td>
<td>0.83 kg</td>
</tr>
<tr>
<td>Mass ratio (granular materials / voided concrete)</td>
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<td>10.5 %</td>
<td>10.5 %</td>
<td>7.0 %</td>
<td>2.3 %</td>
</tr>
<tr>
<td>Type of polyethylene bags</td>
<td>none</td>
<td>thin film</td>
<td>layered film</td>
<td>layered film</td>
<td>layered film</td>
</tr>
<tr>
<td>Layout of granular materials per cavity</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

#### 3.2 Results of experiment

The reduction in vibrations for Cases 1 and 2 are shown in Fig. 4. The reduction refers to the difference in octave band average impedance levels from Case 0. The average impedance is the energy-mean value of transfer impedance at each measurement point (the average value of 13 points).

A reduction in vibrations can be seen under both Case 1 and 2. However, the frequency characteristics are different. For Case 1, the maximum reduction is seen in the 125-Hz band, whereas in Case 2 the maximum reduction is obtained in the 63-Hz band.

The mass of granular materials for these two cases is the same, but the thickness of the bags is different.

Figure 5 shows the vibration distributions. The vibration distribution in the frequency band, in which the maximum reduction was obtained for Case 1 or Case 2, is compared with Case 0.

Vibrations are especially reduced in the antinode of the vibration mode. These changes seem to have occurred as if the internal damping of the concrete slab increased.
As a result of these experiments, it is observed that the frequency characteristics of reductions peak at a specific frequency band. Therefore, it is presumed that vibrations are reduced not by a simple addition of damping, but by a TMD mechanism[2]. The granular materials as the mass, the bag as the spring, and moderate internal damping within them combine to compose a TMD, which can impose a large amount of reduction.

Figure 6(a) shows the driving point impedance level of Case 1 (thin film) and Case 0. Some dips are seen in the impedance characteristics due to vibration resonance of the slab. The dip at 150 Hz in Case 1 is notably shallower than Case 0.

Figure 6(b) shows a comparison between Case 2 (layered film) and Case 0. The dip at 80 Hz in Case 2 is notably shallower.
As mentioned above, vibrations were significantly reduced across a specific range of frequencies. Those frequencies were lower in cases using thicker bags that have a lower spring constant than thin bags. These characteristics can be explained by the TMD theory.

If they are TMDs, the frequency at which a large reduction is obtained should shift if the mass is changed and spring is constant.

The results of Cases 2, 3 and 4 are also shown in Figs. 6(b), 6(c) and 6(d) respectively. The thickness of the bag is the same under these conditions.

The frequency at which the vibration is reduced rises as the mass of granular materials decreases. The estimated resonance frequencies of the TMDs are shown by arrows in Figs. (a) to (d).

Figure 6: Experimental results of driving point impedance

4. Numerical studies using the Finite Element Method

The phenomenon of vibration reduction in a concrete slab with granular materials was studied using the Finite Element Method (FEM).

4.1 Calculation conditions

Figure 7 shows the model for FEM analysis. The concrete slab was modeled using solid elements. The cavities were not simulated; therefore the slab was modeled as a solid slab with equivalent density and equivalent stiffness. To simulate vibration isolation supports, spring elements were used. The granular materials were modeled as TMDs using mass elements and spring elements with dampers. The same number of 102 TMDs were set as in the experiment.
Five calculation conditions for Case 0 to Case 4 were set. They were conditioned to be the same as the experiments. The spring constant of the TMDs for each case was set so that the resonance frequency was equal to that estimated from the experimental results. For thin film, it is set to 3,000,000 kg/s², and for layered film, it is set to 850,000 kg/s². The spring damping coefficient of the TMDs was set to 0.2 under all conditions. The damping coefficient for the concrete internal damping was set to 0.01.

The driving point was set at the end of the slab model, and driving point impedance was calculated from the results of the frequency response analysis.

### Table 2: Conditions for FEM calculation

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Mass</td>
<td>none</td>
<td>3.75 kg</td>
<td>3.75 kg</td>
<td>2.50 kg</td>
<td>0.83 kg</td>
</tr>
<tr>
<td>Spring constant</td>
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<td>850,000 kg/s²</td>
<td>850,000 kg/s²</td>
<td>850,000 kg/s²</td>
</tr>
</tbody>
</table>

### 4.2 Calculation results

The calculated driving point impedance of a slab with TMDs is shown in Fig. 8 compared with Case 0 (without TMD). One of the dips at 150 Hz in Case 1 is shallow (Fig. 8(a)). In Case 2, the dip at 80 Hz is shallow (Fig. 8(b)). These characteristics are similar to the experimental results.

The results of Cases 2, 3 and 4, calculated using the same spring constant (850,000 kg/s²: corresponding to layered film) but a different mass, also demonstrated good agreement with the experimental results (Figs. 8(b), 8(c) and 8(d)). As the mass of the granular materials decreases, the frequency at which the vibration reduction can be observed rises.
5. Conclusions

Reducing vibration resonance in concrete slabs is difficult due to its low internal damping. However, it was found in our experiments that vibrations can be reduced using granular materials and bags.

Logical studies were conducted experimentally. Studies using FEM calculations was also performed. From these results, it was found that granular materials in bags act as TMDs and reduce vibrations in concrete slabs.

On another occasion, we will report on the characteristics of vibrations and floor impact sound in actual buildings in which granular materials were used to reduce structure-borne sound.

REFERENCES