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Evaluation of floor vibrations induced by walking in reinforced concrete buildings

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ABSTRACT

Floor vibrations induced by human walking were investigated in a reinforced concrete structure. Six experimental floor structures were built in laboratories with the same dimensions and boundary conditions. Subjective tests were performed to assess the vibration serviceability of the floor structures. First, the subjects were asked to walk across a floor and then to rate the intensity of the vibrations, acceptability, and serviceability of the floors. In the second part of the tests, the subjects were seated on a chair placed in the middle of the floor and asked to rate floor vibrations when the walker passed the subjects. Floor vibrations induced by human walking were analyzed using peak acceleration, root mean square (r.m.s.) acceleration, and the vibration dose value (VDV), and four weighting functions (W_b, W_k, W_g, and W_m) were applied. Significant differences in the measured floor vibration were found across the floor structures, larger floor vibration lead to greater perceived vibration intensity, lower acceptability and serviceability. The W_b and W_k were found to be more applicable than W_g and W_m to explain perception of floor vibration. It was observed that the impact noise induced by walking did not influence the evaluation of floor vibration.

Keywords: Floor vibration, Human walking, Response to vibration

1. INTRODUCTION

Vibration disturbance in a building comes mainly from external sources such as industrial machinery or transportation; however, internal sources (domestic equipment, doors banging and footfalls) also produce building vibration [1]. In particular, human walking is often of special interest because it is the most common vibration source that occurs inside a building and walking frequency interferes with the natural frequency of the floor resulting in amplitude amplification [2]. Floor vibration induced by human walking is generally small in amplitude but may result in the annoyance and discomfort of the occupants.

Light-weight floors have less mass and lower structural damping than other floors, and these characteristics result in the dynamic response of a floor being greater in both amplitude and

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displacement, which is detrimental to the floor vibration [3]. Long span floors with low natural frequency might also cause floor vibration because humans are more sensitive to low frequencies compared to high frequencies [4]. Therefore, the focus of researchers on floor vibration has been mainly on light-weight floors and long span floors [5, 6].

The most widely used way to reduce floor impact sound in building construction is floating floors. It has been found that a floating floor is effective to reduce light-weight impact noise but limited to reduce heavy-weight impact noise [7, 8]. Recently, thick resilient isolators were introduced for control of heavy-weight impact noise, and a significant increase in heavy-weight impact sound insulation performance was observed with increased thickness of the resilient isolator [9]. A thicker resilient isolator may lead to reduced dynamic stiffness and thus as the dynamic stiffness decreases, occupants are more likely to complain about floor vibration. However, there is little knowledge about the vibration performance and serviceability of floating floors with thick isolators.

The present study was designed to assess floor vibrations induced by human walking in reinforced concrete buildings. A total of six floor structures with different insulating layers were installed in a test building. The subjects were then asked to rate the floor vibrations while they walked across the floor by themselves and when another person walked back and forth on the floor.

2. METHOD

2.1 Test building

In the present study, measurements of floor vibration were conducted in a test building, which is used for practical testing and certification. The building employed a box frame-type structural system and each room had a rectangular shape 4.5 m × 3.5 m. The ratio of the width and length was determined to simulate the living rooms of residential buildings in Korea. A sliding door was in the frontal wall to reflect the boundary condition of the living room. The volume of each room was 37.8 m^3, and the shape of a room was rectangular and all rooms were unfurnished. The reverberation time at 500 Hz was 1.1 s and the background noise levels were less than 23 dBA.

2.2 Experimental floor structures

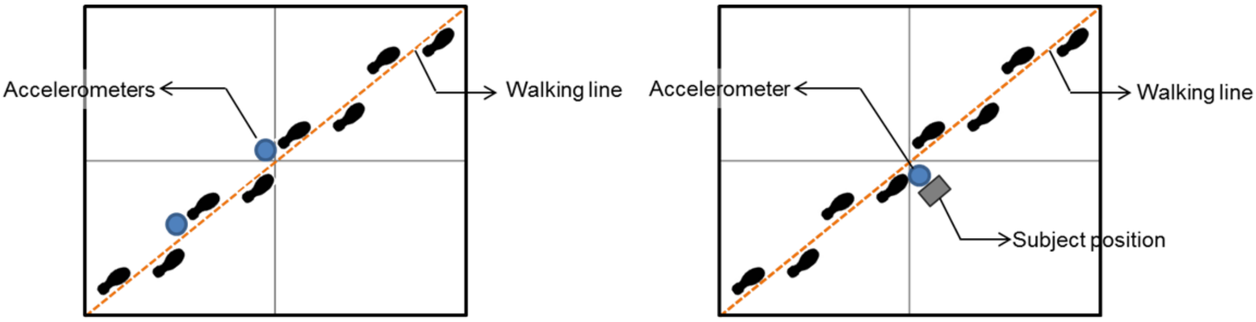
As described in Table 1, a total of six types of floor structures were investigated. Total thickness varied from 290 mm to 330 mm according to the composition of the floor structures. Floors consisted of reinforced concrete slabs, an insulating layer, light-weight concrete, finishing mortar or a precast concrete panel. Four floors had a 210-mm thick reinforced concrete slab, while two floors had a 180-mm thick concrete slab. It was expected that the different compositions of the floor structures would lead to significant changes in the dynamic properties of the floors.

Table 1 – Details of floor structures.

Floor	Total thickness [mm]	Cross-sectional detail
1	320	Concrete slab (210 mm) + Isolator (60 mm) + Mortar (50 mm)
2	320	Concrete slab (210 mm) + Isolator (60 mm) + Mortar (50 mm)
3	290	Concrete slab (180 mm) + Isolator (60 mm) + Mortar (50 mm)
4	290	Concrete slab (180 mm) + Isolator (20 mm) + Light-weight concrete (45 mm) + Mortar (45 mm)
5	330	Concrete slab (210 mm) + Isolator (90 mm) + Precast concrete panel (30 mm)
6	320	Concrete slab (210 mm) + Isolator (60 mm) + Mortar (50 mm)

2.3 Procedure

Walking tests were performed in order to assess the vibration serviceability of the experimental floor structures. Experiments consisted of two walking tests: 1) test with a person’s own walking, and 2) test with another walking person. The subjects walked whilst barefoot because it was assumed that they were in the living room. In the first test, as shown in Figure 1(a), the test subjects were asked to walk across the floor structure themselves, with each travel length about 5.7 m. Once they reached the corner of the room, they turned and walked back to the starting position and repeated each walk once. The subjects needed about 4.5 s to complete each walk, corresponding to a step frequency of 1.7 - 2.0 Hz. The subjects repeated the test wearing ear plugs to examine the influence of sound on vibration perception. In the second test, the subjects were seated on a chair placed at the observation position which was about 30 cm from the center of the room (Figure 1(b)). A walker weighing 68 kg walked back and forth on the floor structure with a step frequency of about 2.3 Hz, and he was asked to make a consistent walking pattern for all subjects. The subjects were asked to rate the subjective perception of floor vibrations when the walker had passed the observation point two times.



(a) (b)

Figure 1 – Walking line and location of the accelerometers: (a) test by a person’s own walking and (b) test by another walking person.

After each test, the subjects were asked to rate the vibration intensity as 1. Imperceptible, 2. Barely perceptible, 3. Distinctly perceptible, 4. Strongly perceptible, and 5. Extremely perceptible. They were also asked to rate the acceptability of the floor structure if it would have been installed in a newly built residential building. They could choose 1. Absolutely unacceptable, 2. Unacceptable, 3. Marginal, 4. Acceptable, and 5. Absolutely acceptable. Finally, they were asked to rate the vibration performance of the floor structure (floor serviceability) on a scale from 0 to 10 (with 0 as ‘very poor’ and 10 as ‘very good’).

In the first test, two accelerometers (KB12VD, MMF) connected to a spectrum analyzer (B&K 2032) and a laptop computer were used to record and analyze the test measurements. During the walking test, one accelerometer was placed near the corner and another was placed near the center of the room. In the second test, only one accelerometer was located near the observation position.

2.4 Subjects

A total of eight subjects (seven males and one female) participated in the experiment. The subjects’ ages ranged from 24 to 36 years (mean: 30.1 and standard deviation: 4.1). The weights of the subjects varied from 43 to 96 kg (mean: 72.3 and standard deviation: 15.8).

2.5 Vibration analysis

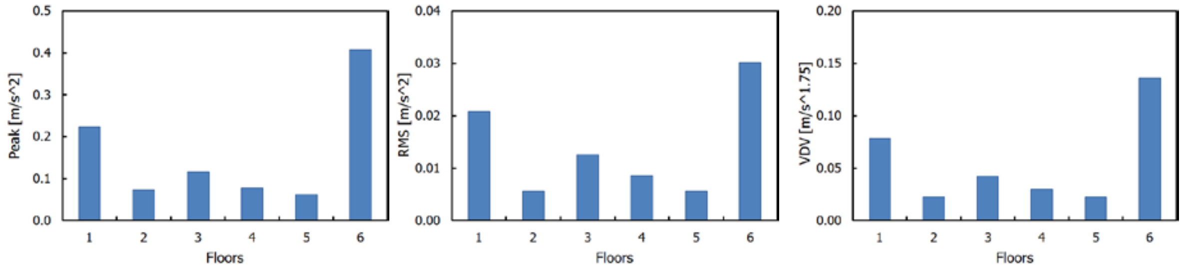
Floor vibrations induced by human walking were analyzed in terms of peak acceleration, RMS of measured accelerations, and vibration dose value (VDV) using *HVLab* software. The length of the measured vibration stimuli were fixed at 4.5 s because the RMS and VDV are time-dependent measures. In the present study, four frequency weightings were used: 1) W_b for vertical vibration based on BS 6472-1:2008 [10], 2) W_k for vertical vibration based on ISO 2631-1:1997 [11], 3) W_g for vertical vibration based on ISO 10137:1992 [12], and 4) W_m for vertical or horizontal vibrations based on ISO 2631-2:2003 [13].

3. RESULTS

3.1 Measured floor vibrations

Figure 2 shows the frequency weighted (W_b) vibrations for the first walking test in terms of peak acceleration, RMS acceleration, and VDV. It was found that the vibration level of floor #6 was significantly greater than the levels of other floors. Floor #1 caused the second largest vibration level followed by floors #3, #4, #2, and #5, respectively. Floors # 3 and #4 with concrete slab thickness of

180 mm showed lower vibration levels than floors #1 and #6 with 210-mm thick concrete slab. This implies that floor vibrations induced by human walking are affected by the composition of the floor structures including the sound insulating layer. The VDVs for the six floor structures and eight subjects were highly correlated with the peak acceleration ($r=0.99$, $p<0.01$) and the RMS acceleration ($r=0.98$, $p<0.01$).

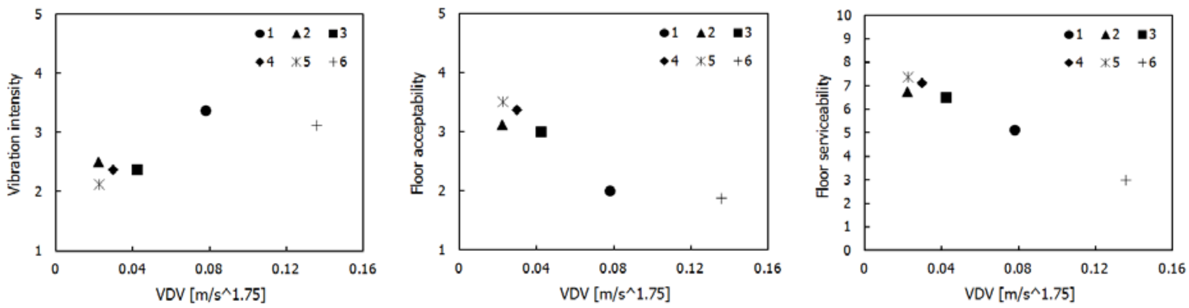


(a) (b) (c)

Figure 2 – W_b weighted floor vibrations: (a) peak acceleration, (b) RMS acceleration, and (c) VDV.

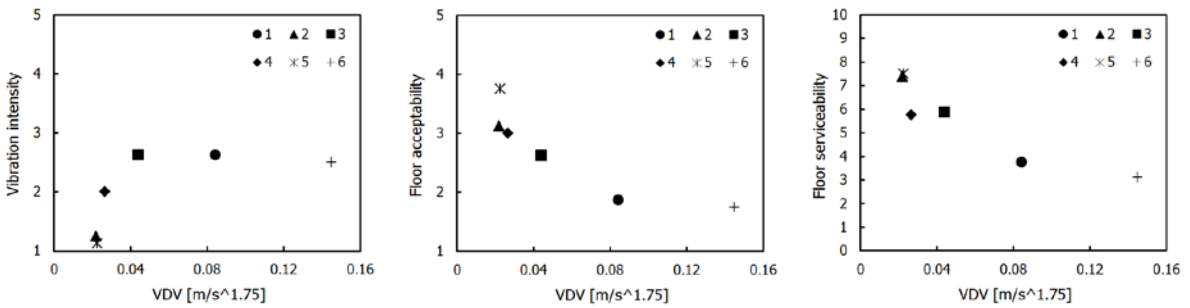
3.2 Perceptions of the floor vibration

Figure 3 presents the perceptions of the floor vibration obtained from a test with a person's own walking as a function of W_b-weighted VDV. The vibration intensity scores increased as the VDV increased. The vibration intensities of floors #1 and #6 were found to be more than '3', corresponding to 'distinctly perceptible'. The perceived vibration intensity for floors #2, # 3, #4, and #5 ranged from 2.1 to 2.5. As expected, the opposite tendencies were found in floor acceptability and floor serviceability. Floor acceptability and floor serviceability ratings decreased with increasing VDV. The ratings of acceptability for floors #1 and #6 were less than '3', which means that they are unacceptable for floors in newly built residential buildings. It was also observed that the serviceability rating of floor #6 was significantly lower than the others.



(a) (b) (c)

Figure 3 – Perceptions of floor vibration for the first walking test as a function of W_b-weighted VDV: (a) vibration intensity, (b) floor acceptability, and (c) floor serviceability.



(a) (b) (c)

Figure 4 – Perceptions of floor vibration for a second walking test as a function of W_b-weighted VDV: (a) vibration intensity, (b) floor acceptability, and (c) floor serviceability.

Subjective ratings for tests by a walking person are illustrated in Figure 4. The ratings of the vibration intensity rapidly increased when the VDV increased; however, they became almost steady with the VDV greater than 0.04 $ms^{-1.75}$. Correspondingly, the ratings of floor acceptability and floor serviceability decreased as the VDV increased. Similar to the first walking test, the ratings of floor acceptability and floor serviceability for floors #1 and #6 were significantly lower than others. Contrary to the first walking test, floor #3 was rated as 'unacceptable' with an acceptability rating of 2.6 in the second walking test. This may be attributed to the difference in vibration level between the center position and the two accelerometers.

4. Discussion

4.1 Weighting functions for floor vibration induced by human walking

Correlation coefficients between objective measures and subjective responses obtained from two walking tests are listed in Table 2. Four different weighting functions (W_b, W_k, W_g, and W_m) were introduced in order to find which weighting function is more appropriate to describe the perception of floor vibration induced by human walking. For the first test with a person's own walking, W_b and W_k had slightly larger correlation coefficients than W_g and W_m; however, the differences between the other weighting functions were not statistically significant. Similarly, the correlation coefficients from different weighting functions were almost the same in the second test.

Table 2 – Correlation coefficients between the objective measures and subjective responses for weighting functions (*p<0.05, **p<0.01).

(a) Test by a person's own walking

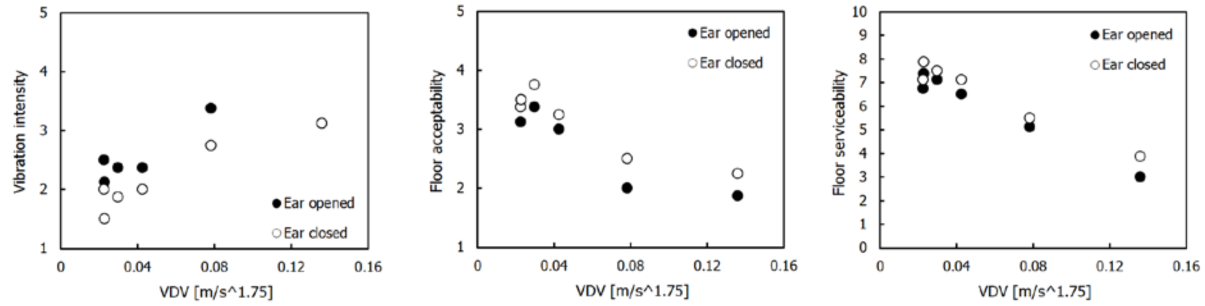
	W_b			W_k			W_g			W_m		
	VDV	Peak	RMS	VDV	Peak	RMS	VDV	Peak	RMS	VDV	Peak	RMS
Intensity	0.80*	0.80*	0.84*	0.79	0.80	0.83*	0.77	0.80	0.80	0.77	0.80	0.80
Acceptability	-0.92**	-0.99**	-0.97**	-0.91**	-0.92**	-0.93**	-0.90*	-0.92*	-0.92**	-0.89*	-0.92**	-0.92**
Serviceability	-0.99**	-0.99**	-0.97**	-0.99**	-0.99**	-0.98**	-0.99**	-0.99**	-0.98**	-0.99**	-0.99**	-0.98**

(b) Test by another walking person

	W_b			W_k			W_g			W_m		
	VDV	Peak	RMS	VDV	Peak	RMS	VDV	Peak	RMS	VDV	Peak	RMS
Intensity	0.65	0.65	0.74	0.65	0.65	0.73	0.64	0.64	0.71	0.64	0.64	0.71
Acceptability	-0.88*	-0.88**	-0.92*	-0.88*	-0.88*	-0.92**	-0.86*	-0.88*	-0.90*	-0.86*	-0.88*	-0.90*
Serviceability	-0.91*	-0.91*	-0.95**	-0.91*	-0.91**	-0.95**	-0.90**	-0.90**	-0.94*	-0.90*	-0.90*	-0.93**

4.2 Influences of the sound on perception of vibration

Human responses to vibrations generated in buildings depend on various factors such as audible noise, visual cues, population type, familiarity with vibration, structural appearance, confidence in a building structure, and knowledge of the source of vibration [12]. Among them, the influence of sound on response to floor vibration was investigated. Subjective ratings with or without ear plugs for the first walking test are illustrated in Figure 5. Independent t-tests were conducted with subjective ratings as a dependent variable and with or without ear plugs as an independent variable. A statistically significant difference between with and without ear plugs was found in vibration intensity ($p<0.05$), whereas there was no difference in vibration acceptability or floor serviceability.



(a) (b) (c)

Figure 5 – Perceptions of floor vibration for first walking test with and without ear plugs: (a) vibration intensity, (b) floor acceptability, and (c) floor serviceability.

5. CONCLUSION

Measured floor vibration levels induced by human walking were significantly different for six floating floors. Subjective ratings of floor vibration were highly correlated with the magnitude of vibration, and the W_b and W_k frequency weightings were found to be slightly better than W_g and W_m frequency weightings in predicting the perception of floor vibration. Judgments of floor vibration were not influenced by the presence of the sound.

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