World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:8, No:6, 2014

Experimental Study on the Floor Vibration Evaluation of Concrete Slab for Existing Buildings

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***Abstract*—** Damages from noise and vibration are increasing every year, most of which are noises between floors in deteriorated building caused by floor impact sound. In this study, the concrete slab measured vibration impact sound for evaluation floor vibration of deteriorated buildings that fails to satisfy with the minimum thickness. In this experimental study, the vibration scale by impact sound was calibrated and compared with ISO and AIJ standard for vibration. The results show that vibration in slab with thickness used in existing building reach human perception levels.

***Keywords*—**Vibration, Frequency, Accelerometer, Concrete slab.

I. Introduction

DAMAGES from noise and vibration are increasing every year, most of which are noises between floors in apartment houses caused by floor impact sound. Limit state refers to a state in which a structure or structural member becomes inappropriate for its intended purpose, and the concept of limit state can be divided into two types. First is ultimate limit state where whole or part of a structure is destroyed or collapsed by reaching maximum carrying capacity to bring serious damage on human life or property, and second is serviceability limit state in which a building is locally damaged or has vibration, excessive displacement and contamination exceed the allowable range to cause failure of the building's functions [1].

In modern architecture, building span is gradually increasing and buildings are becoming light weighted with development of structural analysis techniques and increased strength of structural materials. Rigidity of floor plate, natural frequency, and damping capacity are being reduced. Most of problems on vibration are related to 'serviceability', which causes residents to feel anxious and uncomfortable. Even if a building is safe, people can feel anxious when the building vibrates. Such degree of vibration in a building that cannot be withstood by ordinary people is defined as 'serviceability limit state'[2].

On automobiles and airplanes, passengers show the most unpleasant reaction to movements with frequency of 5~8Hz, which is because the natural frequency of human ribs and abdomen lies within this range and creates resonance. A vibration may not damage a structure, but it can give displeasure to users or affect work process during use of a sensitive machine. Human body is extremely sensitive to vibrations, and people can use fingertips to sense vibrations with amplitude as low as 0.05μmor below.Within the frequency range of 1~8Hz, people are known to begin feeling displeasure at around 0.005~0.01g (0.05~0.10m/sec^2), in case of continuous vibration. For temporary vibration, people feel displeasure at around 0.05g in a structure with 6% damping [3]. Buildings are exposed to vibrations on a daily basis, and the effect of vibrations on structural safety of buildings differs according to various factors such as amplitude and cycle of vibration. Also in general, there is a substantial difference between human perception and safety of building. The standard of heavyweight impact noise interruption performance for standard floor structures was reinforced because of damages from noises between floors, and slab thickness of wall type and mixed structure buildings was increased from 150mm or below to 210mm or above. Regular inspections are performed on buildings that used slab thickness of 210mm or above such as newly constructed apartment houses, but there is lack of inspection and assessment on old apartment houses that used slab with thickness of 150mm or below.

This study was conducted as a reliability study for assessment of floor vibration on slab that fails to satisfy the minimum thickness made for existing old buildings, referring to the criteria of ISO and AIJ [4], [5].

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II. Theoretical Background

A. Vibration

Vibration is mainly transferred to structures through ground. Most of vibration sources are impact sources like construction machines, which are either regular or irregular and temporary or continuous. Sources of vibration impact are generated in the form of shock wave and converted to elastic wave with amplitude and cycle. Here, the elastic wave generated inflicts damage on nearby structures and facilities. Ground vibration is described with displacement, velocity, acceleration and frequency. When a typical form of ground vibration is assumed to be a simple harmonic motion with constant cycle, the correlation is established among displacement, velocity and acceleration at maximum amplitude as follows [6]:

$$\mu = \mu_0 \sin(\omega t + \theta)\ ;\ \int \dot{\mu}\ \ dx \tag{1}$$

$$\mu = \frac{d\mu}{dt} = \omega \sin\left(\omega t + \theta + \frac{\pi}{2}\right);\ \dot{\mu} = \int \ddot{\mu} dx \tag{2}$$

$$\ddot{\mu} = \dot{d}\frac{\mu}{dt} = d^2\frac{\mu}{dt^2} = \omega^2 \mu_0 \sin(\omega t + \theta + \pi) \tag{3}$$

$$\omega = 2\pi f = 2\pi\left(\frac{1}{T}\right) \tag{4}$$

where μ, μ_0 *and* θ *are* displacement or maximum displacement (mm), phase angle(rad). $\dot{\mu}$ *and* $\ddot{\mu}$ are particle velocity(mm/sec,cm/sec,kine) and acceleration($gal, cm/sec^2$). t and ω is time(sec) or circular frequency(angular velocity). f and Tis frequency (Hz) and cycle(sec).

Since the absolute value of maximum particle motion is important in most situations related to characteristics of ground vibration, it can be represented as an absolute value as shown in the following two equations when $\mu max = \mu_0$, $\dot{\mu} max = v, \ddot{\mu} max = a$. As they have a functional relationship, the variable for maximum particle velocity can be computed once vibration frequency is known and vibration is approximately a simple sinusoidal wave by the following equations:

$$v = \omega\mu_0 = 2\pi f \mu_0\ ;\ \mu_0 = \frac{v}{2\pi f} \tag{5}$$

$$\alpha = \omega^2\mu_0 = (2\pi f)^2\mu_0 = 2\pi f v\ ; v = \frac{a}{2\pi f} \tag{6}$$

Also, the relational expression for wavelength λ, propagation velocity of elastic wave c, and cycle T as follows:

$$\lambda = cT = c\left(\frac{1}{f}\right) \tag{7}$$

The attenuation relation of ground vibration for which the functional relationship is established is as follows:

$$V = V(D)^n \tag{8}$$

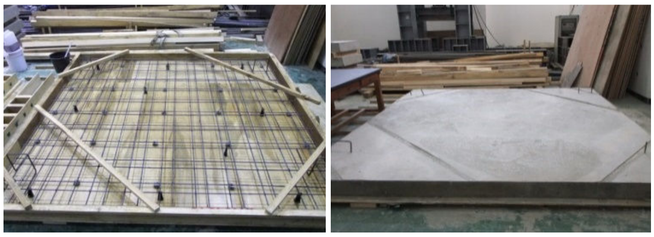
where V is ground vibration velocity (mm/sec, cm/sec). D is distance between station points from vibration source and n is location constant by soil conditions.

B. Fast Fourier Transform (FFT)

Fourier Transform devised by a French mathematician named Fourier is composed of analog signals expressed as Sin and Cos. This is a type of algorithm used by computer to process Fourier Transform at high speed. All analog signals in time domain can be interpreted in frequency domain using A/D (analog to digital) converter. When an analog signal is analyzed in frequency domain, signals with unique size at a specific frequency can be separated.

III. Experiment

Design strength of the specimen for floor vibration assessment of concrete slab is 24MPa, and the specimen was manufactured pursuant to KS F 2865 and JIS A 1440-2 with size of 3200X3200X140mm [7],[8]. D13 rebar was arranged for 28 days of atmosphere curing. For the experiment, a 70kg adult male was allowed to jump from the center every second to inflict impact on the floor, and measurement was done at each point. Measurement as done using accelerometer, and Fast Fourier Transform was performed for comparative analysis with the vibration assessment criteria. Figs. 1 (a) and (b) are mold of floor vibration and specimen of floor vibration.



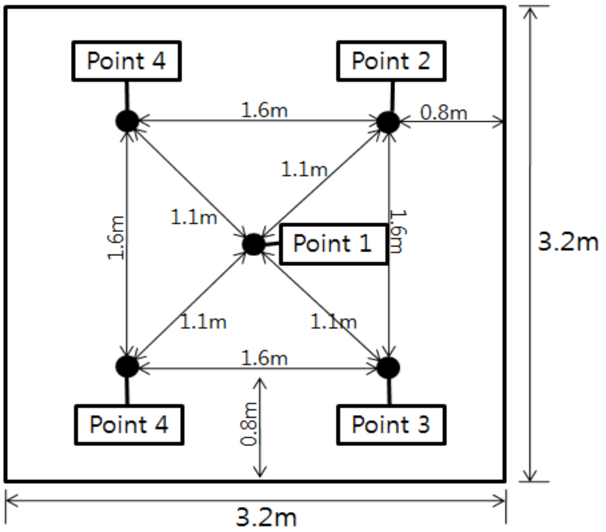
(a) Mold of floor vibration (b) Specimen of floor vibration

Fig. 1 Specimen of vibration measurement

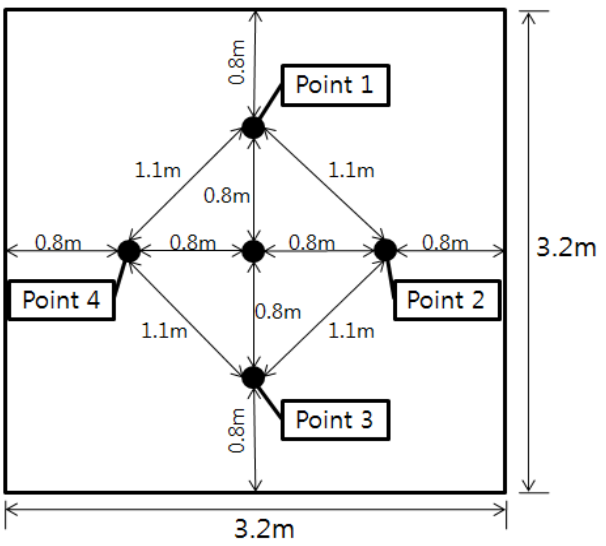
In vibration measurement, selection of an appropriate sensor is the most important aspect. For selection of sensor, dynamic range which includes expected frequency domain of the measurement subject, resonance frequency, signal sensitivity under measurement conditions, and noise level of the sensor must be taken into account. The sensor was installed according to the basic guidelines to maintain horizontality, and it was fixed to an accurate position so that the response axis agreed with the direction of measurement. In addition, since the sensor can be affected by temperature, magnet and electricity, a place that does not receive external influence like nearby high-tension power line was selected for installation. Table I shows the specifications of accelerometer.

TABLE I
Accelerometer Data

Technical data		Type 8784A5
Range	g	±5
Sensitivity, ±10%	mV/g	1000
Frequency response, ±5%	Hz	1…6000
Threshold, nom.	g_{rms}	0,0004
Transverse sensitivity, typ.	%	1,5
Non-linearity	%FSO	±1
Shock (1 ms pulse)	g_{pk}	2500
Temp. coeff. Sensitivity typ.	%/℃	-0,06
Operating temperature range	℃	-55…80
Power supply	mA VDC	2…20 18…30
Housing/base	material	Titanium
Degree of protection (EN60529)		IP68
Mass	grams	21
Ground isolated		With adapt.



(a) Experiment 1 (1/4)

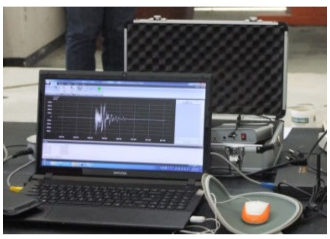


(b) Experiment 2 (1/2)

Fig. 2 Point of vibration measurement

As shown in Figs. 2 (a) and (b), the experiment for vibration measurement using accelerometer was divided into 1/4 point of experiment 1 and 1/2 point of experiment 2. Figs. 3 (a) and (b) show data measurement using accelerometer and Table II is the AIJ residential performance assessment criteria [5].

(a) Accelerometer



(b) Data measurement

Fig. 3 Data measurement by accelerometer

TABLE II
AIJ RESIDENTIAL PERFORMANCE ASSESSMENT CRITERIA

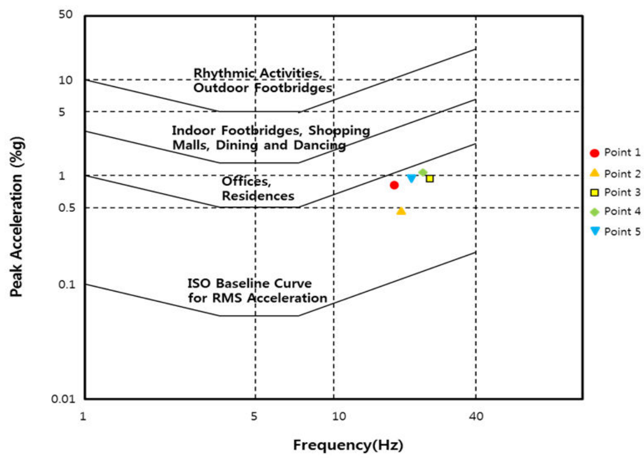
Variety	State of structure	Assessment criteria
Vibration 1	the floor plate of continuous and intermittent vibration by repeatedly vibration	Below V-5
Vibration 2	Floor plate of low the damping by vibration impact (below damping factor, h=3%)	Below V-10
Vibration 3	Floor plate of high the damping by vibration impact (damping factor, h=3~6%)	Below V-30

IV. Experimental Results

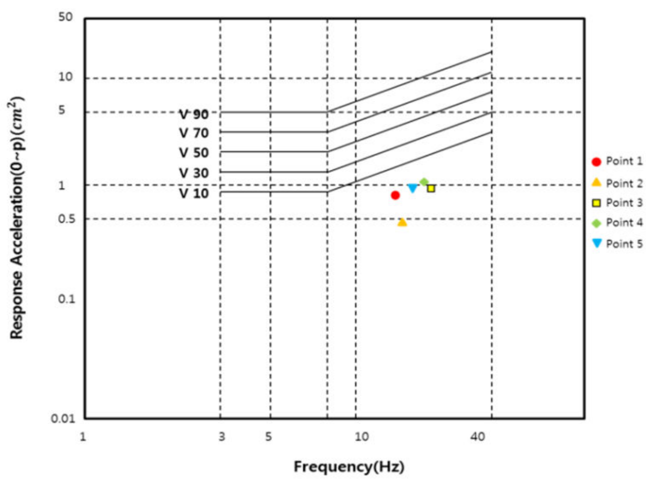
A. Experiment 1

TABLE III
RESULT OF EXPERIMENT 1

Experiment 1	Peak Acceleration (%g)	Peak Frequency (Hz)	Time (sec)	ISO	AIJ
Point 1	0.73	18.5	36	Baseline	Baseline
Point 2	0.47	19.58	29	Baseline	Baseline
Point 3	0.87	22.57	47	Baseline	Baseline
Point 4	1.07	19.5	19	Baseline	Baseline
Point 5	0.87	22.3	60	Baseline	Baseline



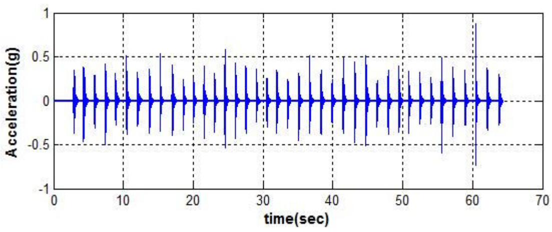
(a) ISO



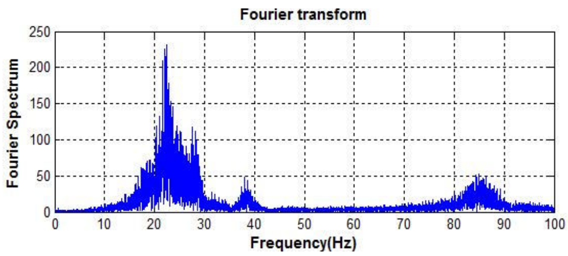
(b) AIJ

Fig. 4 Compare standard of experiment 1

Serviceability value at which people feel discomfort was based on the recommended value of ISO 2603-2. As in Table III, serviceability limit of office and residential spaces at predominant frequencies of 18.5, 19.6, 22.6, 20.0 and 22.3Hz for Points 1~5 is 0.7, 0.5, 0.9, 1.1 and 0.9% of gravitational acceleration. Accordingly, 0.7, 0.5, 0.9, 1.1 and 0.9%g were set as reference values. The highest acceleration amplitudes measured were 0.73, 0.47, 0.87, 1.07 and 0.87%. These values are not close to the recommended values for office and residential spaces. Since the range of vibration was 18.5%~22.57%g, there is no problem in terms of serviceability. Figs. 4 (a) and (b) comparatively analyze the measurements results of experiment 1 with the criteria of ISO and AIJ. Figs. 5 (a) and (b) show the frequency value of Point 5 among experimental values of experiment 1.



(a) Peak Acceleration of Point 5



(b) Peak Frequency of Point 5

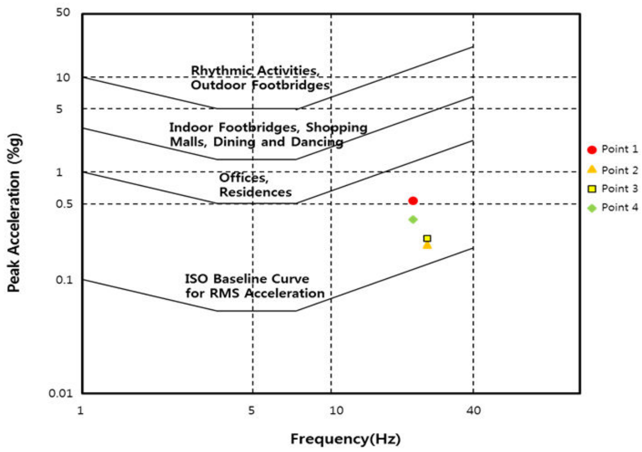
Fig. 5 Frequency value of experiment 1

B. Experiment 2

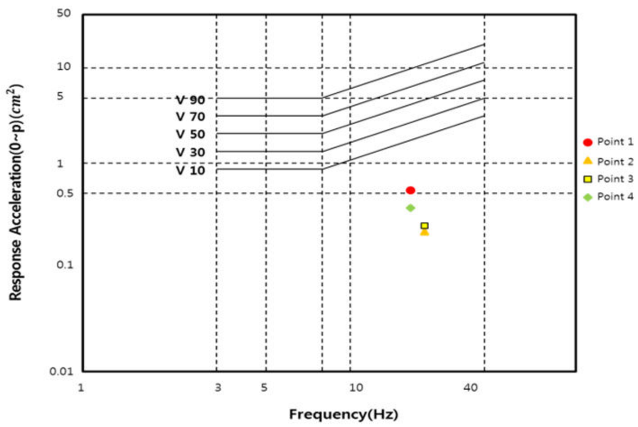
TABLE IV
RESULT OF EXPERIMENT 2

Experiment 2	Peak Acceleration (%g)	Peak Frequency (Hz)	Time (sec)	ISO	AIJ
Point 1	0.73	18.5	36	Baseline	Baseline
Point 2	0.47	19.58	29	Baseline	Baseline
Point 3	0.87	22.57	47	Baseline	Baseline
Point 4	1.07	19.5	19	Baseline	Baseline
Point 5	0.87	22.3	60	Baseline	Baseline

Figs. 6 (a) and (b) compare the measurement results of experiment 2 with the standard criteria. As in Table IV, acceleration values were 0.51, 0.32, 0.35 and 0.41% at predominant frequencies of 19.2, 23.4, 23.5 and 19.5Hz for Points 1~4. Accordingly, 0.5, 0.3, 0.3 and 0.4%g were selected as reference values. The highest acceleration amplitudes measured were 0.51, 0.32, 0.35 and 0.41%, which are further away from recommended values for office and residential spaces than primary measurement. Since the range of vibration was 19.2%~23.5%g, there is no problem in terms of serviceability. Figs. 7 (a) and (b) are the frequency values of Point 1 among experimental values of experiment 2.

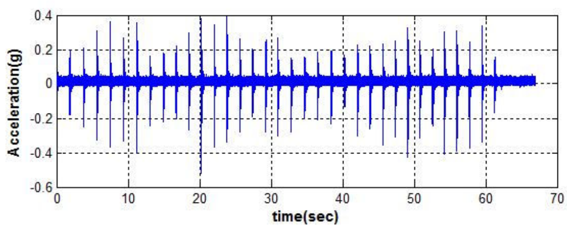


(a) ISO

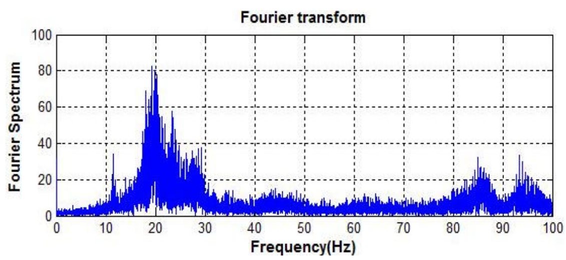


(b) AIJ

Fig. 6 Compare standard of experiment 2



(a) Peak Acceleration of Point 1



(b) Peak Frequency of Point 1

Fig. 7 Frequency value of experiment 2

V. CONCLUSIONS

In this study, an experiment was conducted for floor vibration assessment by measuring impact sound of a specimen manufactured as slab for residential buildings such as old apartment houses. The results are as follows:

1) When the vibration measurement results using accelerometer are compared with the vibration assessment criteria of ISO and residential assessment guidelines provided by Architectural Institute of Japan, vibration currently does not exceed the damage limit or serviceability limit of building. Looking at a cluster of natural frequencies of floor slab clustered around the same range, temporary vibration was found to occur.
2) As a result of conducting the experiment at different measurement points, maximum acceleration was 0.47~1.07%g and maximum frequency was 18.5~22.57Hz for experiment 1 (1/4 point). Maximum acceleration was 0.32~0.51%g and maximum frequency was 19.2~23.5Hz for experiment 2 (1/2 point). Maximum frequency of experiment 1 was relatively higher than that of experiment 2. Attenuation point differs according to the measurement position of vibration wave, and as a consequence, acceleration and frequency of vibration wave were changed. Slab floor with thickness lower than the current standards used in old apartment houses creates living noise at level that does not exceed the standard range, but the noise is sufficient enough to make people feel uncomfortable.
3) Vibration currently does not exceed damage limit or serviceability limit of building, but there is a problem of serviceability for temporary vibration. As natural frequencies were measured to be similar based on the result of vibration measurement performed at various measurement points, buildings can possibly be damaged by vertical vibration and amplification of longitudinal vibration. A future study is deemed necessary to secure experimental data for serviceability and to assess applicability of floor vibration assessment criteria for aged buildings.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MEST) (No. 2012R1A2A2A01012013)."

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