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Measurements of dynamic properties of concrete structures using flexural wave propagation characteristics

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ABSTRACT

Flexural wave propagation characteristics influence the impact noise generation of concrete structures that are found in building floors, railroads, bridges, and many other engineering structures. The flexural vibration of the structure is affected by concrete dynamic properties. The purpose of this study is to measure the concrete dynamic characteristics using a wave propagation approach. The flexural wave speeds, bending stiffness and their loss factors were measured. The measured characteristics are essential for understanding sound radiation and vibration dissipation capabilities of the concrete structures. Various concrete beam structures were made and tested. The dynamic stiffness and loss factor were influenced by its components and showed frequency-dependent variation, especially for the measured loss factor.

1. Introduction

In order to make building structures a safe and quiet residential space, the reduction of noise transferred through the floors is essential. The floor impact noise is generated from the vibration of concrete slabs and floor coverings that are excited by impact sources. The most common noise sources include rotating machineries, running or walking residents. The generated noises have rich low-frequency (50–100 Hz) content (Jeon et al., 2006). Also, the concrete is being applied to wide variety of engineering structures such as railroads, bridges, and tower. The concrete slab usually consists of cement paste, a steel bar, and a combination of coarse and fine aggregates. Its material properties have effects on the structural and vibro-acoustical characteristics. To understand and model the vibration response and noise generation mechanisms, the material properties should be measured in the audio frequency ranges using a relatively simple but accurate experimental method.

Various methods for non-destructive evaluation of concrete dynamic properties have been proposed (Malhotra and Carino, 1991). The resonant frequency method has been used to obtain the dynamic stiffness for flexural vibration of concrete beam (ASTM C 215-02, 2003; Lin and Sansalone, 1992a,b). In this method, the dynamic stiffness was obtained at a single frequency, without information of the loss factor.

Ultrasonic wave propagation has been used to determine dynamic properties of early aged (Sun et al., 2006a) and hardened concretes (Shiotani et al., 2009). This method has been used for different sizes of concrete structures (Piwakowski et al., 2004; Aggelis et al., 2009). But the measured results can be affected from the coarse aggregate when the wave length is comparable to the component size. The impact-echo method which utilizes the stress wave propagations has been used to measure the dynamic characteristics of concrete (ASTM C 597-02, 2003). Longitudinal wave speeds from the resonant frequency of a concrete cylinder were measured at early ages and the method was applied to plate structures (Pessiki and Carino, 1988; Pessiki and Johnson, 1996). The ratio of the wave velocities for plates and rods depends on Poisson's ratio. Direct P-wave speed measurements were performed (ASTM C1383-04, 2004) utilizing the characteristic that the P-wave speed is the fastest type of stress wave. In order to test large specimens other than thin slab concrete, Rayleigh surface wave velocity measurements using the cross correlation function were proposed by Wu et al. (1995). This method is limited to large specimens, since long distances between the source and receiver are required.

Although several different methods using stress wave propagation have been proposed to measure dynamic stiffness, the damping characteristics were not measured. To investigate the damping properties, the modal damping ratio was most often measured (Wang and Zeng, 2006; Carneiro et al., 2006). More detailed measurements of the damping characteristics include measuring the structural loss factor. The measurements of the frequency dependent variation of the viscoelastic properties require measurements of wave propagation characteristics and were

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limited to the cement paste at very early stages (Sun et al., 2006b).

In this study the flexural wave propagation characteristics of the concrete composite structures were measured from the vibration of the specimen. To induce controlled vibration of the concrete beam, it was excited by an impact hammer under free–free boundary conditions. The transfer function between vibrations of the beam was measured. From the measured transfer function, the frequency-dependent variation of the dynamic stiffness and the loss factors was obtained at closely spaced frequency values using the beam transfer function method (Park, 2005). A variety of specimens of different geometries were built and tested. The effects of various parameters on the accuracy of the measured properties were investigated.

2. Effects of floor vibration on the impact noise generation

To investigate the influence of the floor vibration characteristics on the impact noise generation, experiments were performed on the actual building structure. Fig. 1 shows the building section. The building was constructed as a box frame-type reinforced concrete structural system. The floor area was 5.1 m × 4.5 m wide and the volume of the receiving room was 62.2 m^3. The thickness of the floor concrete slab was 0.21 m. For investigation of the vibro-acoustic properties, modal testing was performed. The center of the floor was excited by the impact hammer (Dytran, 5803A), and the resulting vibration of the floor was measured by the accelerometers (Endevco, 751-10) at 30 uniformly distributed locations. Fig. 2 shows the shapes of (1, 1) and (2, 1) modes. The natural frequencies of (1, 1) and (2, 1) modes were 32.5 and 61.4 Hz, respectively. In this frequency range, the bending deformation dominates the flexural response of the floor panel.

To measure the forced responses, heavy-weight impact sound and vibration was measured using the heavy/soft impact source known as the Impact ball (ISO 140-11). The center of the source room was excited by the impact source as shown in Fig. 1. An accelerometer was installed at the center of ceiling, and the microphone was placed at the center of the floor and 0.12 m above the receiving room floor. The vibration and sound radiation were measured simultaneously as shown in Fig. 3. The resonant responses of the sound pressure occurred at resonance frequencies of the vibration responses. The first and second resonant responses correspond to those of the (1, 1) and (2, 1) natural modes measured from the modal tests. Although the acoustic mode of the room had a little influence on the measured sound pressure, the floor natural modes of bending vibration had dominant effects on the noise generated by heavy-weight impact sources. Consequently, the flexural vibration characteristics of the floor should be analyzed for reduction of the impact noise generation.

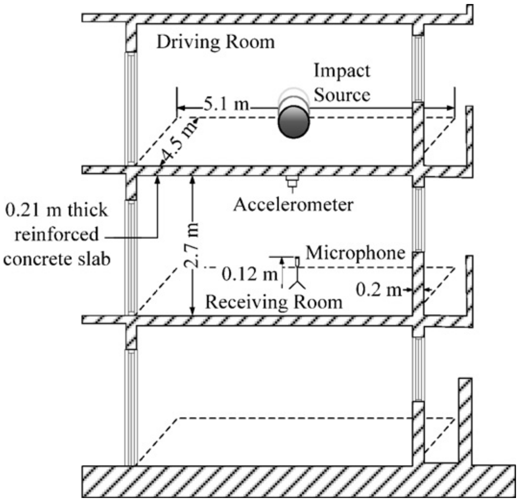
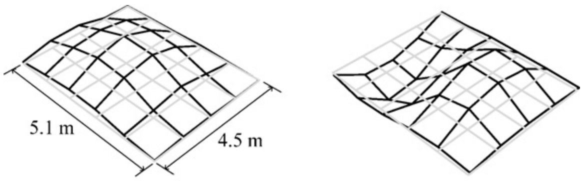


Fig. 1. Measurement set-up in the test building section.



(a) 1x1 mode (b) 2x1 mode

Fig. 2. Mode shape of 210 mm thick concrete slab: (a) 1 × 1 mode and (b) 2 × 1 mode.

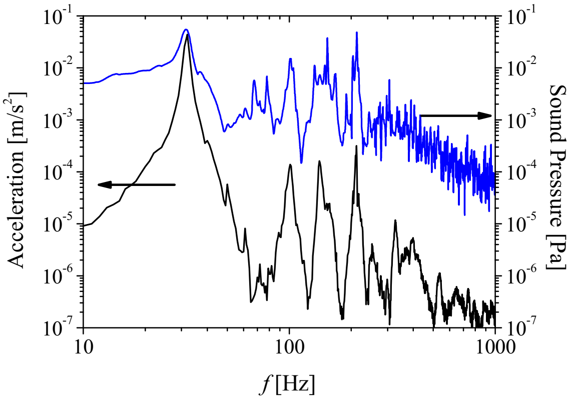


Fig. 3. Vibration and sound radiation from a solid concrete floor excited by a soft impact source.

3. Flexural vibration of concrete structures

When the effects of shear deformation and rotary inertia are negligible, compared to those of bending deformation, the equation of motion for vibrating beams is

$$D\frac{\partial^4 w}{\partial x^4} + M\frac{\partial^2 w}{\partial t^2} = 0, \tag{1}$$

where $D = EI$, in which E is the dynamic modulus and I is the cross-sectional area moment of inertia, and M is the mass per unit length of the beam. Assuming harmonic motion, i.e., $w(x, t) = Re\{\hat{w}(x)e^{i\omega t}\}$, the complex stiffness is widely used to model the dissipation of vibration energy within a structure. The complex bending stiffness, $\hat{D}$, is obtained by measuring the complex modulus of the beam materials, $\hat{E} = E(\omega)[1 + i\eta_E(\omega)]$. From the given values of the elastic properties and geometric parameters, the resonant vibration of the concrete structure is analyzed using numerical methods such as FEM, statistical energy analysis, or the Rayleigh–Ritz method. During resonant vibration, which is the most significant contributor to noise or excessive vibration of structures, the loss factor has a significant impact.

Several methods have been proposed to measure the dynamic mechanical properties of materials. In the low frequency range, dynamic material test systems are commercially available for the measurement of the complex moduli. These systems can have very limited application for materials with large stiffness such as fully cured concrete. A measurement method that is based on standing longitudinal waves was proposed and standardized (Pritz, 1982; Madigosky and Lee, 1983; ANSI S2.22-1998, 1998). When measuring the complex moduli of metal or concrete samples, these methods have limitation due to high natural frequencies of longitudinal vibration modes. These problems can be resolved when the complex bending stiffness is measured directly. The resonant