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# Cause and perception of amplitude modulation of heavy-weight impact sounds in concrete wall structures

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A B S T R A C T

This study investigated amplitude-modulation effects on the heavy-weight floor impact sound caused by a vibration of concrete wall construction. The fundamental resonance of a floor in concrete wall construction consists of two closely spaced vibration modes. These modes were identified from experimental modal analysis of an actual multi-story building. The modes corresponded to in-phase and out-of-phase vibrations of the upper and lower floors. The rigidity of the side walls had influence on the difference between the natural frequencies of the two modes. Low-frequency modulated sounds were generated in a room by the simultaneous excitations of the two vibration modes. The heavy-weight impact sounds were analyzed using auditory experiments to determine the amplitude-modulation effects on the perceived annoyance. The highly modulated impact sounds were judged to be 3–5 dB more annoying than the one having the same level without modulation. Consequently, impact sound transmission from floors connected by less rigid side walls exhibited lower annoyance.


## 1. Introduction

In multi-story buildings, heavy-weight impact sounds caused by walking, running or jumping are important sources of noise transmission through floors. To ensure quiet and private residential space, efficient sound insulation methodologies are required to minimize this structure-borne sound transmission as well as airborne noise. Several standard impact sources, such as bang machines and impact balls, have been proposed to evaluate the sound insulation performance of a floor [1]. Recent studies have shown that the impact ball sounds are more similar to real human-made impact sounds than other standard impact sources both in level and temporal characteristics [2]. Multi-story apartments in Korea are built with concrete wall structure or framed-structure. More than 50% of the housing in Korea consists of multi-story reinforced concrete residential buildings. Concrete wall structures contain walls to carry loads, in contrast to framed-structures which are designed for carrying axial loads through columns and beams [3]. The concrete wall structure is advantageous for reducing construction costs and periods, and is more common in residential apartment buildings in Korea. Heavy-weight impact sounds in concrete wall structure are louder and yield greater annoyance than those in framed-structure buildings [4,5]; however, the difference in the sound generation mechanism is not fully understood. The parameters having influence on the sound generation should be investigated in order to propose practical soundproofing methods of minimizing the impact sound transmission into multiple layers.

The modal property of the floor vibration especially the fundamental (1st) structural mode [6] and the acoustic room modes [7] are primary factors influencing the heavy-weight sound transmission. The finite element method was used to calculate the reduction in floor impact vibration for the floor structures of apartment buildings built using resilient materials [8]. In these numerical models dynamic coupling between upper and lower concrete floors were neglected. The modal properties of several heavy-weight impact sources were measured and used to investigate the excitation forces from the source to the floor [9]. The transient and resulting spectral characteristics of the impact force were analyzed after estimating the modal mass and spring. Mechanical impedances of impact sources and floors were used to estimate the sound insulation performance [10].

Heavy-weight floor impact sounds have been evaluated according to the sound pressure level (SPL) in the frequency range of 63–500 Hz. Single-number rating values, such as the $L_{i,F\max,AW}$

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(inverse A-weighted impact SPL), $L_{Fmax}$ and $L_{A,Fmax}$ have been calculated on the basis of the maximum SPL [11,12]. In addition to these temporal characteristics, the effects of a spatial factor on the subjective responses to heavy-weight floor impact sounds were investigated through the magnitude of an interaural cross-correlation function of sounds as measured in a concrete wall construction built with reinforced concrete slab floors [13,14]. These noise indices are determined by only the SPL, which is categorized into temporal factors, and do not include any of the spatial attributes of the sound field.

The relationship between subjective response to floor impact sounds and noise evaluation index was investigated, and it was reported that percentile loudness, N10, and Zwicker's loudness were highly correlated with the subjective response to impact ball sounds [15]. Owaki et al. proposed $L_{Aeq}$ as a descriptor for bang machine sounds, because $L_{Aeq}$ was more highly correlated with subjective responses than maximum sound level indices such as $L_{max}$ and $L_{A\ max}$ [16]. Jeon and Sato investigate the annoyance of heavy-weight impact sounds using the autocorrelation function (ACF) parameters, loudness and fluctuation strengths [17]. Jeon and co-workers classified heavy-weight impact noise excited by impact ball into three groups according to frequency characteristics, then investigated the subjective response to each group using SQ metrics [18–20].

Previous studies that have analyzed heavy-weight floor impact sounds have neglected amplitude-modulation in both the modeling and evaluation of impact noise transmission. However, the heavy-weight impact sounds in multi-story buildings are generally amplitude-modulated in the audio frequency range. The modulation significantly affects the perceived annoyance for continuous harmonic sounds [21]. For heavyweight impact sounds, the amplitude-modulation occurs from vibration interactions between floors and side walls. In this study, twin modes at the first resonances of concrete wall structure are measured for actual multi-story buildings. The twin modes correspond to structural modes of the upper and lower concrete floors interacting through the supporting concrete walls. Vibration characteristics were analyzed using experimental modal analysis with excitation at the upper floor. The mechanism of the modulated sound generation for the concrete wall structure was investigated, and mechanical and geometrical factors that influence the modulation frequency were analyzed. How these factors affect perceived annoyance was investigated by auditory experiments and noise level was estimated by $L_{max}$ and $L_{A\ max}$ according to Korean standard (KS F 2810) [1]. Virtual heavy-weight impact sounds having different modulation frequencies were produced for the experiments. A paired comparison method was applied to quantitatively determine the annoyance. Statistical analysis was conducted to correlate the modulation frequency and the perceived annoyance. With this approach, the cause of modulation and its effect on annoyance of heavy-weight floor impact sounds were analyzed.

## 2. Vibration characteristics of floors and side walls and their influence on the generation of modulated sound

### 2.1. Vibration characteristics of concrete wall structure and resulting sound radiation

To verify the existence and contribution of modulated impact sounds in actual concrete wall structure, experiments were performed in a standardized testing room at the Korea Institute of Construction Technology Center, Fig. 1. The room has dimensions of 5.1 × 4.5 × 2.85 m, and the floor and side wall thicknesses were 0.21 and 0.15 m, respectively. When the upper floor was excited by an impact ball after dropping from 1 m height at slightly side of the center for avoid modal point, the resulting vibrations at the same locations on the upper and lower floors were measured simultaneously using accelerometers (ENDEVCO Model 2250A-10), as shown in Fig. 1(a). The sound radiation was measured at the same location as the accelerometer and 1.2 m above the floor using a microphone (B&K pressure microphone 4187). The testing room is shown in Fig. 1(b).

The lower floor and side walls vibrated simultaneously due to the vibration energy transferred through wall connections when the upper floor is excited by the heavy-weight impact source. Noise radiation occurs from these wall vibrations [22–24]. The modal properties of floors have a significant influence on the radiated sound. Fig. 2 shows the measured vibration and sound radiation from the impact ball excitation. The twin peak of first natural frequency was measured as 28 Hz and 33 Hz. At this resonance, the vibration and radiated sound pressure was greatest, and there were two resonance peaks rather than one. To distinguish this twin resonance modes, a fine frequency resolution during frequency transform was required. The upper floor vibration response was larger since the response phases for each modes were in phase at the excitation location (upper floor) [25]. At the lower floor, the response phases were out of phase for each mode, and the vibration amplitude (the difference between contributions from two modes) was smaller. The damping in the construction also contributes to the larger response of the upper floor. The lower floor vibrated due to the vibration energy transferred through side wall connections. Impact sound radiation occurs from these vibration modes and has similar frequency spectrums as shown in Fig. 2. Although it was smaller than those of the upper floor, the lower floor vibration response was also significant and contributes to the radiated sound in the receiving room.

To further investigate the twin modes, experimental modal analysis was performed after measuring the vibrations at four evenly spaced locations (1 m apart) on the upper and lower floors with a hammer (B&K Modal Sledge Hammer 8210) excitation at the center of the upper floor. To enhance the accuracy during estimation of mode shapes, the vibration of floors were measured simultaneously using four accelerometers installed both in upper and lower floors. Fig. 3 shows the identified mode shapes at each resonance peak. The mode shapes were identical for each mode, but the lower floor movements directed oppositely between the two modes. The two floors moved out-of phase at the lower resonance mode. At the higher resonance mode, the two floors vibrated in phase. This suggested that the twin resonance peaks are actual physical characteristics of the floor vibration rather than an experimental error, and requires a fine frequency resolution for the modal analysis.

The impact force generation during impact ball excitation was measured in the previous study. Fig. 4 shows the measured force and its frequency spectrum for the impact ball used in this study. Procedures for measuring the impact force were detailed in the reference [9]. The first natural frequency of the impact ball was 24 Hz, and the resulting excitation force was similar to the half sine curve as in the force generation of a mass spring system to the ground. The measured impact force showed a lower level of higher spectrum peaks compared to main fundamental spectrum centered at frequency ranges between 10 and 70 Hz. Due to this low frequency excitation to the floor, the response of the twin modes having small natural frequencies were much greater than those of the higher order vibration modes. The second resonance above the twin resonance peaks were 56 Hz, but there magnitudes were smaller due to lower excitation force of the impact ball as shown in Fig. 4(b), and fast decay of the higher order modes from vibration damping.