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Effect of structural vibration and room acoustic modes on low frequency impact noise in apartment house with floating floor

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ABSTRACT

In today's apartment houses, adoption of floating floor has vastly improved structure-borne floor impact noise by isolating vibration components well in excess of the major structural vibration resonant frequencies. For 20–200 Hz frequency region encompassing major structural vibratory and room acoustic modes, however, impact noise attenuation is much harder to achieve, and the problem can be exacerbated for small rooms where these modes are sparsely placed in audible frequency range. Experimental and numerical investigation of the effect of structural vibration and room acoustics on impact noise for the frequency region is undertaken. Structural vibration modes of the room with floating floor correlate well with the spectral characteristics of the impact noise, with various structural parts making different contributions in the frequency domain. For the low end of the impact noise spectrum, low density of high-energy axial room acoustic modes arising from small room size causes sound field in the room to show notable variation with measurement locations. For the mock-up typical of a small-sized living room considered in the present study, one of the vibrational mode of floor slab excites an overlapping fundamental room acoustic mode that further amplifies the impact noise. A room design that avoids overlapping of major structural and acoustic resonance modes at low end of the audible spectrum could be crucial in abating an echo commonly encountered in bare apartment rooms.

1. Introduction

In recent years, the inter-floor noise in apartment houses has become an important community issue. Codes and regulations have been drawn up in many industrialized countries to resolve inter-floor noise disputes that are becoming more prevalent [1–3]. Many research works for mitigating the problem are in progress. The inter-floor noise phenomenon can be divided into air-borne and structure-borne sound depending on the type of sources [4,5]. The air-borne sound is transmitted through boundaries separating household units and can be mitigated by sound insulation measures such as inserting insulating materials between walls [6]. The primary source of the structure-borne sound is the sound radiated [7–9] by an impact force that causes vibration of the floor in the unit located directly above [8,10]. The floor impact noise can be mitigated by embedding a layer of shock-absorbing resilient material in the floor. In Korea, the Ministry of Land, Infrastructure and Transport maintains the code for floor construction in apartment houses [7]. The code mandates a floating floor constructed of layers of surface finishing material, mortar, aerated concrete, resilient cushion material and concrete slab of appropriate thicknesses.

The level of floor impact noise is influenced by floor composition and thickness, shape of the room, and physical characteristics of resilient materials [11,12]. In particular, the dynamic stiffness of resilient material – defined as the ratio of dynamic loading over dynamic displacement – is known to play a prominent role in the abatement of inter-floor noise [13,14]. Many investigations to elucidate the effect of the dynamic stiffness of resilient material, are being carried out [15,16]. For measuring the dynamic stiffness, Korean Industrial Standard [17] that combines features of the international standard [18] and Japanese standard [19] was introduced in 2003.

Internationally, ISO 10140 and ISO 16283 series stipulate methodology and process for floor impact noise measurement [20,21]. In the measurement of floor impact noise, ISO10140-3 stipulates the use of a tapping machine [20]. In Korea, the domestic standard makes a distinction between the light-weight impact

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sound and the heavy-weight impact sound depending on the source of the impact force and the frequency range involved. For the light-weight impact sound, the domestic standard uses a tapping machine just like the international standard and the sound measurements are for octave bands with the center frequencies of 125–2000 Hz [20–22]. To measure heavy-weight sound, measurement for octave bands with center frequencies 63–500 Hz are stipulated [23]. Since the source of inter-floor noise in Korea and many Asian countries is often a person walking in bare foot, the actual load can be quite different from the excitation force profile stipulated in ISO standards [9,24]. Numerous investigations have considered the load characteristics of a person walking or a child running in bare foot [8,25,26], and the bulk the load spectrum is found to lie in 1–200 Hz range [25]. A research result has also suggested that an impact ball gives somewhat closer approximation of a bare foot impact than a bang machine [26]. For the heavy-weight impact noise, which is established to more closely assess the low-frequency sound, the domestic standard KS F 2810-2 [23] stipulates the measurement techniques using "Bang machine" or "Impact ball" while KS F 2863-2 defines a process for evaluating impact noise [27].

For both the light-weight and heavy-weight impact noise types, impact is applied is at a 750 mm distance from the edges at each of the four corners of the room, as well as at the dead center of the room. For a room size less than 59 m^2, however, the distance is reduced from 750 mm to 500 mm from the edges at the corner. The five microphones located at the same locations one floor down measure the resulting impact noise at the height of 1.5 m. For the heavy-weight impact noise, the maximum noise level is measured, while for the light-weight impact noise, the mean noise level is measured [7,28].

A layer made of resilient material in floating floor is known to be generally effective against both the light-weight and heavy-weight impact noise [29,30]. For modern apartment housing units in Korea, the impact noise in excess of 200 Hz is known to be effectively mitigated by the vibration isolation due to the introduction of floating floor [7]. The present study therefore focuses on the frequency range of 20–200 Hz which forms the low end of the impact noise and encompasses major structural vibration modes as well as isolated, high-energy room acoustic modes. The size and the shape of a mock-up used in the present study correspond to a living room common to small-medium apartment housing units in Korea. The effect of structural modes on the impact noise is investigated by employing experimental measurements of the mock-up and the analysis of a numerical model of the mock-up. Where appropriate, the role played by room acoustic modes is investigated as well. Numerical prediction of the inter-floor noise is carried out by applying SIEMENS Virtual Lab. Ver. 13.6.

2. Theory

2.1. Impact noise in a receiving room

A room in apartment housing unit is composed of floor, ceiling and walls made of concrete slabs. Since the ratio of the thickness to the lateral dimension of the slab is 0.05–0.1, the floor and walls can be modeled as a plate [31]. Since impact on the floor causes vibration of small amplitude, the resulting elastic deformation of the floor can be obtained by applying the thin plate theory due to Kirchhoff [32].

For a simple room constituted of a concrete slab at the top and acoustic cavity underneath shown in Fig. 1, the radiated sound power in the room can be theoretically estimated. For a thin-plate model, the radiated sound power is directly related to the transverse vibration and affected by the mechanical and radiation

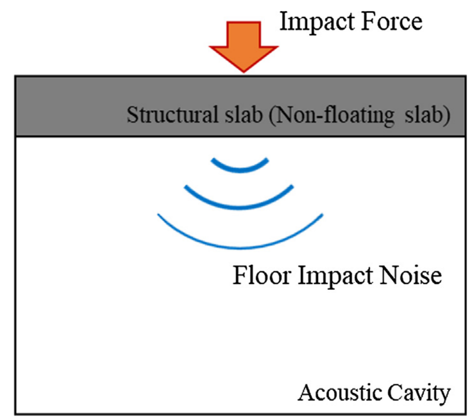

Fig. 1. Generation of floor impact noise.

properties of the slab. For an impact force F, the resulting radiated sound power can be expressed by [30,33],

$$W_{rad} = \frac{0.43F^2\rho_0 c_0}{\rho_p^2 C_L \eta h^3 \omega}\sigma_{rad} \tag{1}$$

where ρ_0 is the density of air, c_0 is the velocity of sound in air, $\rho_p$is the density of the slab, $C_L$is the propagation speed of the longitudinal wave, η is the loss factor of the slab, h is the thickness of the slab, ω (=2πf) is the angular frequency, and $\sigma_{rad}$is the radiation efficiency of the slab.

For the room, multiple reflections form a diffuse sound field, and the dissipated sound power can be expressed by

$$W_d = \left(\left\langle P^2\right\rangle/4\rho_0 c_0\right)A_0 \tag{2}$$

where P denotes sound pressure in the room, and A_0 is the reference absorption area [34]. Assuming there is no energy loss in the room, i. e., assuming that the energy equilibrium exists, the radiated power can be set equal to the dissipated power, and Eqs. (1) and (2) yield the octave-band mean-squared sound pressure level in the receiving room given by

$$L_n(f) \equiv 10log\left(\frac{\left\langle P^2\right\rangle}{P_{ref}{}^2}\right) = 10log\left(\frac{0.27F^2(\rho_0 c_0)^2\sigma_{rad}}{P_{ref}{}^2 A_0 \rho_p^2 C_L h^3 \eta f}\right) \tag{3}$$

In summary, the sound pressure level for each octave band for the non-floating floor can be theoretically estimated by Eq. (3), where $P_{ref} = 2 \times 10^{-5}$ N/m^2. Theoretically, the sound level diminishes by 9 dB if the thickness of a non-floating slab is doubled [35].

2.2. Impact noise reduction of floating floor

Impact noise can be reduced by designing in a floating floor. Fig. 2 shows the standard floating floor structure in which resilient material is sandwiched between concrete slabs. To distinguish from a non-floating simple slab structure of Fig. 1, the upper slab

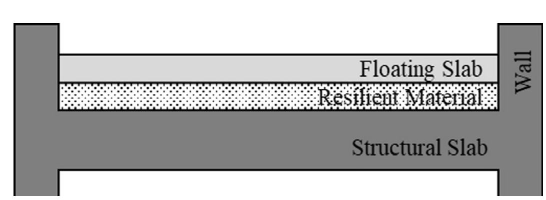

Fig. 2. Structure of floating floor.