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Low-frequency impact sound transmission of floating floor: Case study of mortar bed on concrete slab with continuous interlayer

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ABSTRACT

The vibroacoustic behavior of a commonly used floating floor installed in an actual multifamily housing unit was investigated to determine the factors that influence impact sound transmission at low frequencies. A finite element vibration model of the floor structure and an experimental sound field against a rubber ball impact were analyzed in combination. The results indicated that, in addition to isolation of the impact energy above the system's natural frequency, the aspect of coupled and decoupled wave fields of the floating floor influences the impact sound transmission. The coupled wave field below the natural frequency is dominated by the bending wave field of the base slab and exerts a strong influence on the sound field, in which the sound field is dependent on the modal space and impact location of the coupled motion. The decoupled wave fields generated in the floating plate or the base slab above the natural frequency may disturb the vibration isolation. The non-rectangular acoustic cavity is considered to mitigate the influence of axial room modes on the impact sound field.

1. Introduction

Low-frequency human footfall noise transmitted from the upper-floor to lower-floor dwelling units has been reported to be one of the hindrances to acoustic comfort in multifamily buildings [1–4] and has remained a long-standing problem to be solved. The frequency band in the vibration from human footsteps is generated by a force normal to the surface and concentrated in the low frequency range below 100 Hz [1,5]. This low frequency impact sound transmission arises regardless of the structural system of building; conventional North American wood-frame constructions [1,6] or concrete structural floor system [2,3,5].

Most sound radiated by vibrating structures is caused by bending (flexural) waves traveling through beams, plates, and shells [7]. Therefore decreasing mobilities of the load-bearing floor members in flexure is the fundamental solution for reducing floor impact noises. The flexural mobility of infinite plates or beams is inversely proportional to the Young's modulus, density and thickness of the members [7,8]. In addition, the mobility at resonance decreases with increasing loss factor (damping) [7]. In case of finite systems, the mobility is influenced by the peripheral boundary conditions [1,9]. Because the elastic and damping properties of the materials commonly used for floor members (i.e. concrete and wood) are difficult to change, reducing the mobility requires structural changes such as span shortening [1] or section enlargement [10], which is economically and practically difficult and unattractive [1].

Accordingly, the use of a floating floor is considered to be a useful method for reducing impact sound transmission without changing structural design because it isolates the impact on the floating plate from the load-bearing floor members [8,11]. The added floor floats on an elastic medium placed upon the load-bearing floor members. Floating floors are generally considered to be a vibration-isolation system that consists of two masses (floating and base plates) and a spring (elastic medium) [12]. When the added plate is significantly more flexible than the bottom reference plate, which is commonly the case in floating floor construction [8], the vibration isolation system establishes three response regions upon the impact on the added floating floor; unity transmission (below the system's resonance frequency, f_n), amplification (at f_n), and isolation (above f_n). The elastic component typically used for

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floating floors is a continuous layer of mineral wool, plastic foam, etc. [12,13]. The dynamic stiffness of the common elastic layer [13–16] is appropriate for reducing impact sounds of greater than 100 Hz because the f_n of the isolation system is formed below 100 Hz in case of massive floating floor (e.g. mortar bed) with continuous interlayer [3,17].

However, the low-frequency (below 100 Hz) vibroacoustics of the common floating floors has not been thoroughly investigated. Blazier and DuPree [1] investigated floating floors in wood-frame residential construction and reported that the fundamental natural frequency of the floor/ceiling system is the important factor for the low-frequency components of footfall noise. Using laboratory tests, Kim et al. [3] showed that the heavy weight impact sound level decreased as the dynamic stiffness of resilient materials decreased, which indicates that the vibration-isolation model of floating floors may be applied to the low-frequency range. Neves e Sousa and Gibbs [18] investigated the effect on impact sound transmission at low frequencies for rectangular rooms in terms of the location of the impact, type of floor, edge conditions, floor and room dimensions, position of the receiver and room absorption. Cho [17,19] investigated the in situ resonance of floating floors with a very low natural frequency of the isolation system (below 20 Hz) and its influence on impact sounds. Although the previous studies investigated a number of factors regarding the low-frequency impact sound transmission of floating floors, the vibroacoustics of floating floors that can account for the field circumstances of impact sound transmission in the low-frequency range is still ambiguous. The obscurity of the low-frequency behavior causes difficulties in the design and field application of floating floors.

Through a case study of a reinforced concrete (RC) multifamily housing unit, this study aims to investigate the impact sound transmission of a commonly used floating floor in the low-frequency range, which would help to elucidate the factors that influence the field performance of floating floors against low-frequency impacts such as human footsteps. The remainder of this paper is organized as follows. Section 2 introduces the floating floor installed in the RC bearing wall structure apartment building, and it presents the experimental method and the results of low-frequency impact sound measurements. Section 3 presents the finite element (FE) analysis of the tested floating floor for the examination of the vibration field and discusses the vibroacoustic factors in the impact sound transmission through the analysis combined with the sound field measurements. The factors involved in the low-frequency impact sound transmission of the floating floor are discussed in Section 4. Section 5 summarizes the findings of the study.

2. Sound field generated by rubber ball impact

2.1. Measurement method

The floating floor was installed between the upper-floor and lower-floor dwelling units in a twenty-story RC bearing wall structure apartment building. Fig. 1 illustrates the plan configuration and cross section of the floating floor. The gray cross-shaped area indicates the floating floor region, which has no constraints on the entire edges. The cross-shaped floating floor is disconnected from lateral floating floors at the structural wall locations and doorframes, which gives free boundary conditions at the edges of the floating floor.

The thick solid lines in Fig. 1(a) indicate the bearing wall locations, where the slab and wall structurally connect, and the dotted lines indicate non-structural walls. The lightweight porous concrete under the mortar bed is the most widely used type of floating floor in Korea, and it forms a laminated composite plate. The lightweight concrete is used for thermal insulation because of its practical and economical efficiency. The dynamic stiffness and loss factor of the expanded polystyrene (EPS) used for the continuous resilient layer were 11–13 MN/m^3 and 0.1, respectively, which are in the range of common EPS produced for resilient purposes [15].

A rubber impact ball, which is recommended by the standards [20–22] for simulating human footsteps, was used to excite the floating floor. The impact force of the standard rubber ball gradually decreases as the frequency increases and is concentrated at below 100 Hz. Fig. 2 shows the rubber ball drop and sound pressure measuring positions in the experiment. The impact positions are designed to represent human footfalls on three sections: living room, kitchen and the space between them. The solid lines in Fig. 2(b) indicate sound reflecting hard wall surfaces (including both structural and non-structural). The microphone at the lower corner of the cavity (M0 in Fig. 2(b)) was used to examine the existence of axial room modes in the living room. Table 1 lists the possible axial room mode frequencies (below 100 Hz) in the acoustic cavity in the dwelling unit. The microphone array (M1–M6) was designed to examine the sound field free from the possible room modes: The microphones are located at 5/16 of the distance between two facing walls and at 3/16 of the distance between the ceiling and floor, which excludes the nodes and antinodes of the room modes along the width axis and the height axis. The microphone configuration along the length axis (7.8 m) was designed to be equally spaced to examine the distribution of the sound pressure along the axis. The impact positions (S1–S3) and microphone positions (M1–M6) also follow the recommendation of the standard [21].

Fig. 3 shows an example of the time series of sound pressure recorded at microphone M4 against the impact on S3. The sound pressure is transient according to the force generation characteristics of the rubber ball impact [23]. Figs. 4 and 5 show the frequency spectra of the impact sound measured at M1–M6 and M0, respectively. Considering the uncertainties in low-frequency field measurements, the spectra were averaged over five impacts at each impact position.

2.2. Analysis of the sound field

Osipov et al. [24] and Prato and Schiavi [25] studied the effects of the coupling between the wall modes and room modes on airborne sound transmission. Neves e Sousa and Gibbs [18] investigated similar coupling between the modal behaviors of a floor and the receiving room below the floor in the impact (structure-borne) sound transmission. These studies indicate the influence of the receiving room modes on the amplification of the transmitted sound energy. Sound pressure at the corner microphone (Fig. 5) does not indicate the occurrences of the 1st/2nd width axis modes in the living room and the 1st height axis mode (see Table 1 for the room mode frequencies). This may imply that the non-rectangular (i.e. cross-shaped) acoustic cavity attenuates the generation of the axial room modes: the sound energy is less trapped and more diffused in the cross-shaped cavity. The axial modes along the length axis (7.8 m), which can be identified from the M1–M6 array if occur, is also not observed in Fig. 4. The fact that the living room is partly open to the balcony (no window installed at the measurement) may contribute to the absence of the length axis modes in addition to the influence of the non-rectangular cavity. The absence of the receiving room modes is considered to weaken the coupling effect between the structural and acoustic modes. However, the coupling effect could be significant in case of rectangular cavities of the receiving room as the previous studies [18,24,25] indicate. The reverberation time of the receiving room is considered to have little influence on the changes in sound pressure below 100 Hz (e.g.