J Wood Sci (2008) 54:285–288
DOI 10.1007/s10086-008-0956-6

ORIGINAL ARTICLE

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Psychoacoustical evaluation of floor-impact sounds from wood-framed structures

Received: September 12, 2007 / Accepted: January 28, 2008 / Published online: April 19, 2008

Abstract Floor-impact sounds may introduce noise problems in dwelling-type environments. In particular, floor-impact sounds from lightweight structures like wood-framed buildings should be paid significant attention. In this study, such floor-impact sounds were investigated from the viewpoint of residents. The floor specifications of wood-framed structures were improved by using high-density underlay, and heavy floor-impact sounds were evaluated by using both psychoacoustical and conventional methods. The results showed that the floor-impact sound insulation grades specified in the Japanese Industrial Standards (JIS) did not correspond to the floor specifications of wood-framed structures. The nonstationary loudness, which is a psychoacoustical index for nonstationary sounds, changed with the specifications of wood-framed structures in a wider range of floor-impact sound levels in comparison with the maximum A-weighted sound pressure level, which is a single-number index of the JIS.

Key words Floor-impact sound · Wood-framed structure · Psychoacoustics · Nonstationary loudness · Maximum A-weighted sound pressure level

Introduction

Wood-framed structures are relatively light in weight and low in stiffness compared with reinforced concrete or other structures, and their sound insulation performance should be improved. It is particularly important to insulate floor-impact sounds from the viewpoint of dwelling comfort.

There are two kinds of impact sources for testing the floor-impact sound insulation of buildings defined by Japanese Industrial Standard (JIS A 1418-1, 1418-2:2000). One is a light and hard impact source, which is the tapping machine specified in ISO 140-7, and the other is a heavy and soft source, like an automobile tire or a rubber ball. The floor-impact sound insulation of buildings is usually evaluated by measuring the sound pressure levels with these impact sources.

From the resident's point of view, the sound insulation performances of buildings have been investigated by using physiological and psychological responses to light floor-impact sounds generated by the tapping machine,[1–4] and heavy floor-impact sounds generated by dropping an automobile tire.[5,6] Moreover, psychoacoustical analysis has been applied to evaluate the floor-impact sounds of a wooden house[5,7] and of a concrete slab with attached damping materials.[8,9] For loudness, which is one of the psychoacoustical evaluation indices, both stationary and nonstationary sounds are defined. The former is standardized by ISO 532B, while the latter has almost been standardized through revision of ISO 532B. Floor impact sounds are classified as nonstationary and can be indicated quantitatively by nonstationary loudness.

In this study, we compare the indices used to evaluate the heavy floor-impact sound insulation of wood-framed structures. Heavy floor-impact sounds for several floor systems generated by dropping an impact source from different heights were examined by comparing the nonstationary loudness with the floor-impact sound insulation indices specified in JIS A 1419-2:2000.

Experimental

Measurement of floor-impact sounds

Figure 1 shows the diagram of a wood-framed structure fixed on a reinforced concrete structure. The wood-framed structure consists of flooring (Japanese cedar, 190 mm in width, 30 mm in thickness) and underlay (asphalt sheet, 455 × 910 mm; 4, 8, and 12 mm in thickness, density = 3 g/cm^3) screwed onto the beams (Douglas fir, 105 × 240 mm), as shown in Fig. 2. The beams were fixed on the concrete

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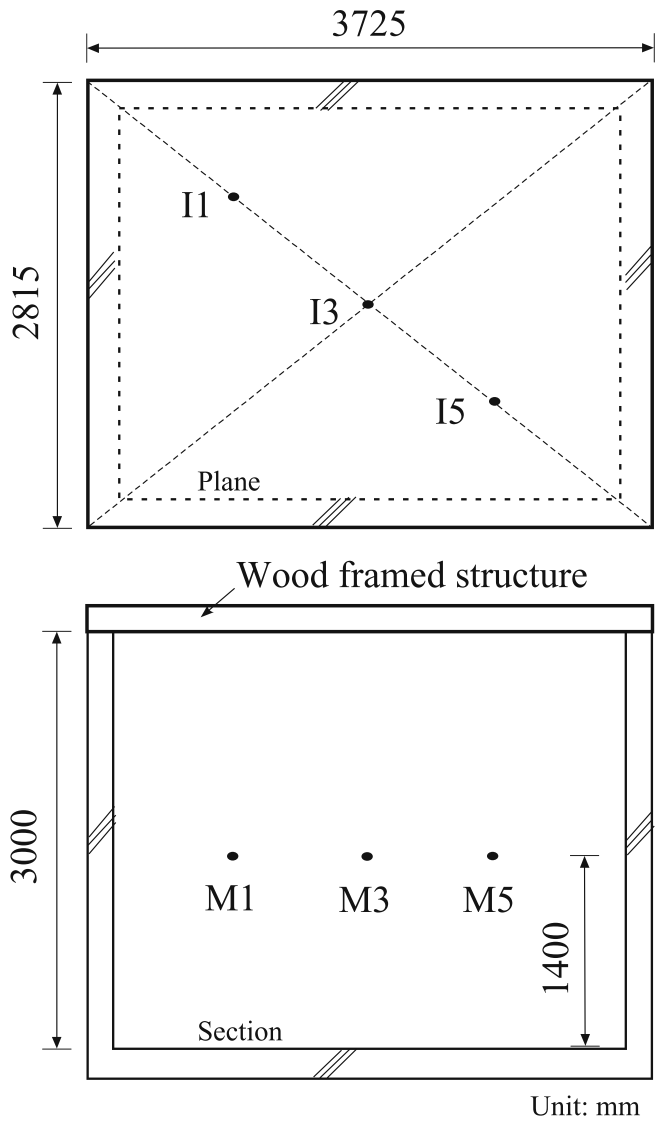

Fig. 1. Diagram of a wood-framed structure fixed on a concrete structure. *I1–I5*, Floor-impact positions; *M1–M5*, sound pressure measuring positions

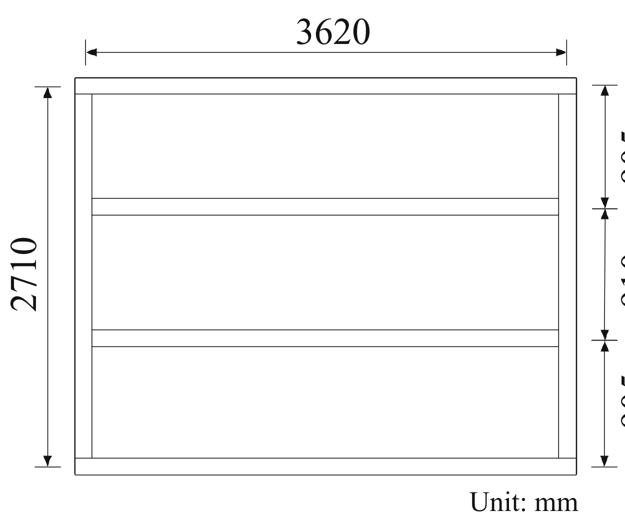

Fig. 2. Beam layout of a wood-framed structure

Table 1. Sectional specifications of wood-framed structures

Specimen no.	Component
Type 1	30-mm-thick flooring
Type 2	30-mm-thick flooring + 30-mm-thick flooring
Type 3	30-mm-thick flooring + 4-mm-thick underlay + 30-mm-thick flooring
Type 4	30-mm-thick flooring + 8-mm-thick underlay + 30-mm-thick flooring
Type 5	30-mm-thick flooring + 12-mm-thick underlay + 30-mm-thick flooring

structure with bolts. The specifications of wood-framed structures in general are shown in Table 1.

A standard-weight impact source having the impact characteristics (2) stipulated by JIS A 1418-2:2000 was used, because this impact source, which is referred to as a "rubber ball" and weighs 2.5 kg, is easy to handle and suitable for lightweight structures like wood-framed structures. Although the standard heavy impact source as specified in JIS was not intended to correctly reproduce the impact of walking, it was used for simulating walking impact in the present study.

Floor-impact sound levels were obtained by using the measuring software for building acoustics in the PULSE SYSTEM (Brüel & Kjær, Type 3560C) based on JIS A 1418-2:2000, and floor-impact sound insulation grades were determined by JIS A 1419-2:2000.

Psychoacoustical analysis

According to psychoacoustics,[10] there are two essentially different regions of stimulus that are processed in the human auditory system. The first region of the hearing system is a peripheral one, where the oscillations keep their original character and preprocessing occurs. The peripheral preprocessing structures have nonlinearities and they send the preprocessed oscillations to the sensory cells, which have nerve terminals that encode the mechanical and electrical stimuli into electrical action potentials. There, the second region begins using neural processing which finally leads to auditory sensations.

Psychoacoustical analysis provides the simulation of nonlinear peripheral preprocessing; for example, the effects of time duration on loudness, and temporal and spectral masking. In the case of the development of loudness for a short tone burst, the tone impulse of 100 ms in duration produces a loudness that is about twice as large as the loudness of the 10-ms impulse.[11] Masking plays a very important role in everyday life. An example of temporal masking is the way in which a large noise disturbs a quiet conversation. A typical example of spectral masking is shown in Fig. 3.[12] A test tone under each curve is just masked by each level of band noise with a center frequency of 1 kHz.

In psychoacoustics, the level of 40 dB of a 1-kHz tone was proposed to give the reference for loudness sensation, that is, 1sone. The level of the 1-kHz tone in a plane field has to increase by 10 dB in order to enlarge the sensation

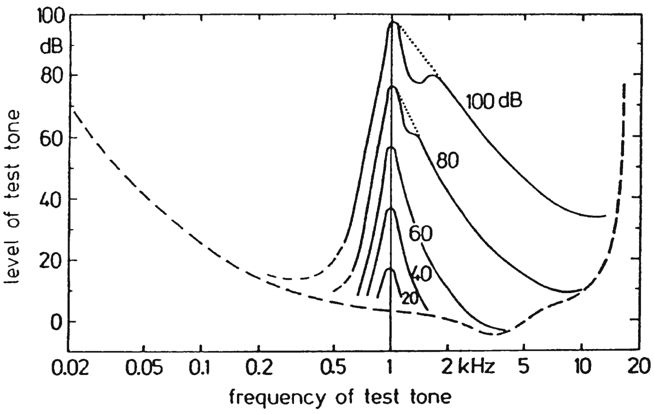

Fig. 3. Level of test tone just masked by a band noise with center frequency of 1 kHz and different levels as a function of the frequency of the test tone. From Fastl and Zwicker[12]

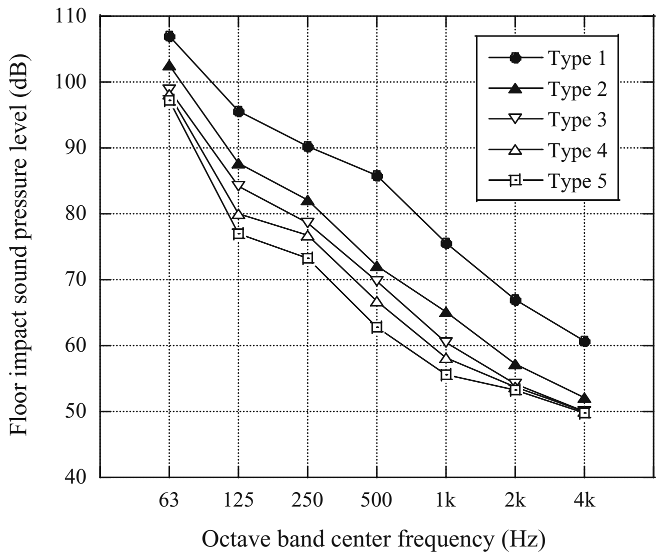

Fig. 4. Variation of floor-impact sound level generated by dropping a rubber ball from a height of 100 cm. Specifications of *Types 1* to *5* are shown in Table 1

of loudness by a factor of two. For example, the sound pressure level of 40 dB has to be increased to 50 dB in order to double the loudness, which then corresponds to 2sone.

Floor-impact sounds were generated by dropping the rubber ball onto the wood-framed structure from heights of 50, 100, and 150 cm and the sound was recorded at each floor-impact and sound-pressure-measuring position with a sound level meter (Brüel & Kjær, Type 2238) and a DAT recorder (Sony, PC216AX). Each sound was then stored in a personal computer as a WAVE file. Using PAK System software (Mueller-BBM), the nonstationary loudness of each floor-impact sound was obtained in consideration of the nonlinear peripheral preprocessing in the human auditory system mentioned above. The maximum A-weighted sound pressure level was simultaneously calculated in the PAK system.

Results

Effect of high-density underlay on floor-impact sounds from wood-framed structures

Figure 4 shows the variations of heavy floor-impact sound levels as a function of octave band center frequency. The sectional specification of wood-framed structures Types 1 to 5 are shown in Table 1. The dominant frequency of floor-impact sound generated by dropping the rubber ball is at the 63-Hz octave band. The performance of floor-impact sound insulation is generally improved from Type 1 to Type 5 because of the increasing mass of the floor, and this fact resulted in the decrease of floor-impact sound level through all the octave bands. The floor-impact sound level at the 63-Hz octave band changed from 107 dB (Type 1) to 97 dB (Type 5).

Psychoacoustical evaluation of floor-impact sounds

Figures 5 and 6 show the variation of maximum A-weighted sound pressure level and nonstationary loudness as a function of type of specimen, respectively. The varied parameter is the height from which a rubber ball is dropped. As mentioned above, the performance of floor-impact sound insulation is generally improved from Type 1 to Type 5, so both indices decrease from Type 1 to Type 5.

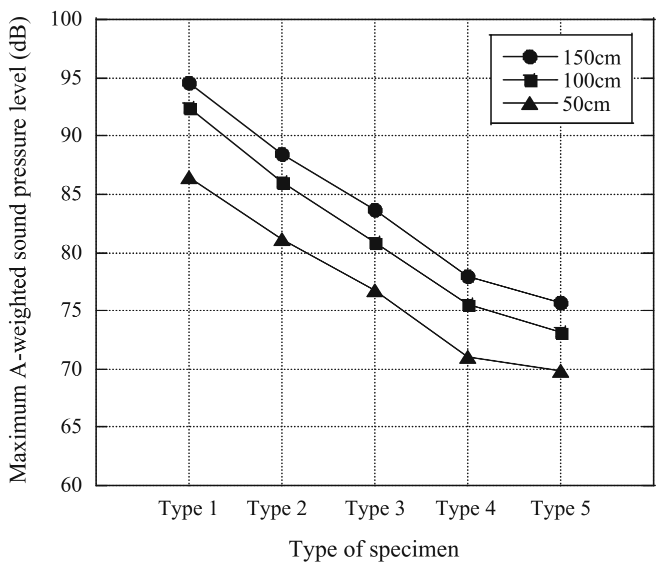

Fig. 5. Variation of maximum A-weighted sound pressure level of floor-impact sounds generated by dropping a rubber ball from heights of 50, 100, and 150 cm

Discussion

In general, the floor-impact sound insulation of buildings is graded according to JIS A 1419-2:2000, like Lr-50, 60, 70, 80, and so on. The smaller grade number of Lr means the

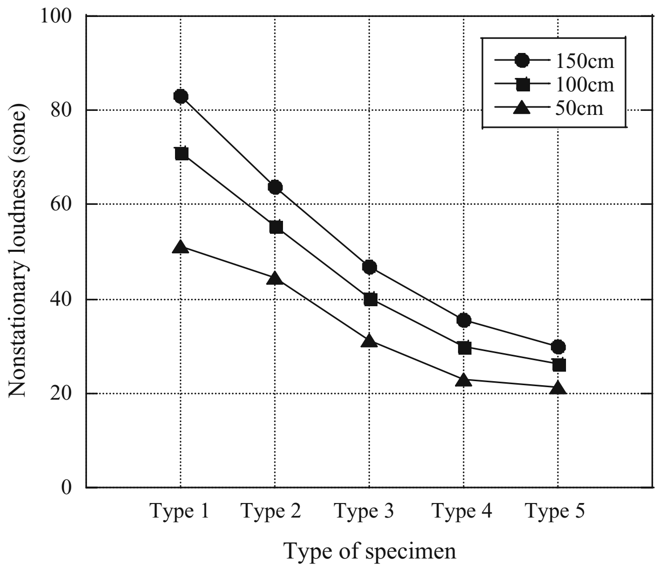

Fig. 6. Variation of nonstationary loudness of floor-impact sounds generated by dropping a rubber ball from heights of 50, 100, and 150 cm

higher performance of floor-impact sound insulation. The floor-impact sound levels of Types 1-5 shown in Fig. 4 are graded as Lr-85 for Type 1, Lr-80 for Type 2, and Lr-75 for Types 3 to 5. These JIS grades were determined by the floor-impact sound level at the 63-Hz octave band and do not correspond to the variation of floor-impact sound levels of Types 3 to 5 through the 125-Hz to 1k-Hz octave bands.

As shown in Fig. 5, the maximum A-weighted sound pressure level, which is one of the indices provided by JIS A 1419-2:2000, varied with the type of specimen and can be used as an index of floor-impact sound insulation. However, the differences between the maximum A-weighted sound pressure levels at 100 cm and 150 cm are less than 3 dB. In particular, the difference in the case of Type 1 is 2.1 dB, which indicates that it is difficult to distinguish the floor-impact sounds by hearing.

Figure 6 shows the change in the nonstationary loudness as a function of the type of specimen. Increases in nonstationary loudness from 100 cm to 150 cm are 17%–19%, and are equivalent to an increase of more than 5 dB in sound pressure level.[5]

It is pointed out that A-weighting has a frequency dependence that corresponds to that of the equal-loudness contour at low levels around 40 dB, and that A-weighted sound pressure level approximates the loudness level only for sinusoidal tones or narrow-band noises at lower levels. Therefore, dBA values of noises like floor-impact sounds at higher levels are misleading when used as indications of subjectively perceived loudness.[13] On the other hand, nonstationary loudness is based on the human auditory system and depends on frequency content and time duration. These facts may cause the difference in variation of the maximum A-weighted sound pressure level and nonstationary loudness at higher levels.

Conclusions

Nonstationary loudness, which is a commonly used index for psychoacoustical evaluation, is more capable of clearly and quantitatively identifying the floor-impact sound insulation of wood-framed structures than JIS indices like the floor-impact sound insulation grades and the maximum A-weighted sound pressure levels. The floor impact sounds from wood-framed structures can be precisely evaluated by nonstationary loudness in the wide ranges of both the type of specimen and the impact energy.

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