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A THEORY ON IMPACT NOISE EVALUATION OF A WOOD JOIST FLOOR FROM EQUIVALENT CIRCUIT MODELS AND PRINCIPLE EXPERIMENT

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For the purpose of decreasing an impact sound level in the room below in a house, a new fundamental study on the impact sound of floors is given in the case of a wood joist floor above the structural concrete slab. In Japan, we have so many opportunities to use wood joist floors in housing. The wood joist floor is convenient and suitable for our Japanese life style. From such a practical viewpoint, a wood joist floor above the reinforced dense concrete floor is considered. Especially a new theoretical trial based on the introduction of equivalent concentrated constant circuit models of electric and mechanical types for an impact noise transmission of a wood joist floor is proposed first. Thus, a practical evaluation of the impact noise reduction can be theoretically estimated by the model method proposed. In the case of a wood joist floor using a resilient material under the wood joist, a quantitative improvement in the impact noise reduction has been systematically expected. Then, from an experimental viewpoint, we have succeeded in confirming the validity of our theory, especially in the case of the I.S.O. standard tapping machine. As a result, we have found a fairly good agreement between our theory and the principle experiment.

1. Introduction

We have so many noise problems in dwelling houses, such as footfall noise, water closet noise etc. Especially, this kind of structure-borne sound is one of the most difficult noise problems to reduce. It is more practical to use the wood joist floors in almost all houses in our country. In both the wooden frame structure and reinforced concrete structure, these kinds of floors are very often used. The wood joist floor is thought to be suitable and comfortable for our Japanese life style, taking off shoes on the high floor in houses. From these practical viewpoints, the wood joist floor above the reinforced concrete slab is considered in this paper. But, it seems to us that any of theoretical studies based on the introduction of the equivalent circuit model for such an impact noise reduction of wood joist floor have not been found so frequently up to now, even in its fundamental aspect [1 – 4]. So, a fundamental study on the impact sound of floors is given in the actual case with wood joist floor on the structural concrete slab, for the purpose of reducing the impact sound level of wood joist floor in the room below, for the daily life sound environment. A main part of this paper is focussed on some new theoretical trial based on the equivalent lumped constant type electric circuit model and also an equivalent mechanical circuit model for an impact noise transmission of wood joist floor is proposed, especially in the fundamental viewpoint. Then, this study is confirmed by some principle experiment with the impact noise reduction of floors in houses excited with the I.S.O. standard tapping machine [5].

2. Theoretical considerations

The mutual characteristics of the impact sound level of the upper room and the lower room is shown at first, in Fig. 1. When the floor of the upper room is tapped by a hammer with force F_1, the radiated sound power W_1 from the floor to the upper room is expressed as follows:

$$W_1 = \alpha_1 F_1^2. \tag{1}$$

Also the relationship between the sound pressure p_2 and the total power in the lower room, taking into consideration the transmission power through floor τW_i, is expressed as follows:

$$\alpha_2 F_1^2 + \tau W_i = \frac{\langle p_2^2 \rangle R_2}{4\rho c}, \tag{2}$$

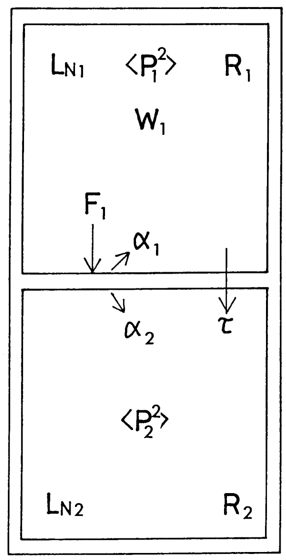

Fig. 1. Structure configuration.

where $W_i = W_1 S/R_1$, R_1 and R_2 are room constants, ρc is the acoustic impedance, τ is the transmission coefficient, and S is the floor space. If β is defined by $\langle v^2\rangle = \beta\langle p^2\rangle$, where v is the vibrational velocity of the floor, there is some transmission power from the upper room to lower one. The transmission coefficient τ is calculated as follows:

$$\tau = \frac{W_t}{W_i} = \frac{\rho c\langle v^2\rangle S\sigma_{\mathrm{rad}}}{\dfrac{\langle p_1^2\rangle S}{4\rho c}} = 4(\rho c)^2\sigma_{\mathrm{rad}}\beta_1\,, \tag{3}$$

where σ_{rad} is the radiation coefficient of the floor. According to the definition of the normalized impact sound level [5], we could obtain the sound level for the lower room as follows:

$$L_{N2} = 10\log\frac{4\rho c\alpha_2 F_1^2 + 4\rho c\tau W_i}{p_0^2 R_0}\,, \tag{4}$$

with $p_0 = 2\times 10^{-5}\,\mathrm{N/m^2}$, $R_0 = 10\,\mathrm{m^2}$.

The sound transmission loss is given by $TL = 10\log(1/\tau)$. If the ratio $\alpha/\beta = \rho ck^2/4\pi$ $(k=\omega/c)$, calculated by Heckl *et al.* [6] and $\sigma_{\mathrm{rad}} \simeq 1$ (in the general case) are introduced into Eqs. (3) and (4), we obtain the summation of L_{N2} and TL in the lower room as follows:

$$L_{N2} + TL = 10\log\left\{\frac{k^2F_1^2}{4\pi p_0^2 R_0}\left(\frac{\alpha_2}{\alpha_1} + \frac{16\pi\rho c\alpha_1 S}{k^2R_1}\right)\right\}. \tag{5}$$

This expression includes a force of the tapping hammer and vibrational velocity of the floor [7].

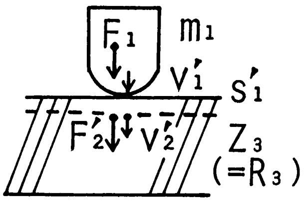

Fig. 2. A simulated model of the impact sound of floors for a bare concrete floor.

Secondary, the improvement of impact noise reduction of floors is usually expressed by the sound level difference in the lower room between the impact sound level of floors generated by a bare concrete floor tapping and the impact sound level of floors generated by a wood joist floor tapping above the structural concrete slab. In the case of a wood joist floor structure, almost all of the tapping vibrational energy from the wood floor is transmitted to the structural concrete slab through the wood joist. First, the vibrational energy transmission is considered in the simulated model of an impact sound of bare concrete floor which is illustrated in Fig. 2. In this case, the equivalent electric circuit model and also the equivalent mechanical circuit model for an impact noise transmission of a bare concrete floor are shown in Fig. 3. Here, m_1 is the mass of the standard tapping machine hammer, F_1 is the force of the tapping hammer, v_1' is the vibrational velocity of the surface of the concrete floor, s_1' is the dynamic stiffness of the surface of the

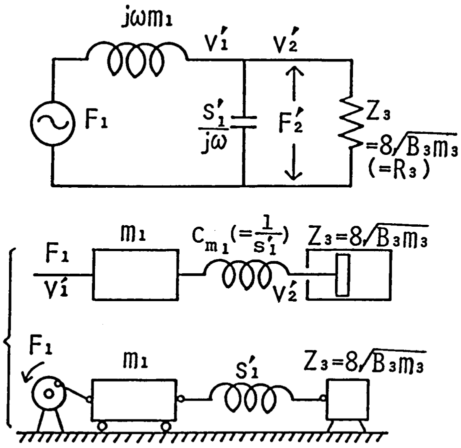

Fig. 3. An equivalent electric circuit model and an equivalent mechanical circuit model for the impact noise transmission of a concrete floor.

concrete floor and the hammer, F_2' is the force (acting) of the concrete floor, v_2' is the vibrational velocity of the concrete floor, and Z_3 is the impedance of the concrete floor. Thus, the vibrational velocity of the surface v_1' can be easily derived by a simplified circuit calculation of the model in Fig. 3 as follows:

$$v_1' = \frac{F_1\left(\dfrac{j\omega}{s_1'} + \dfrac{1}{Z_3}\right)}{1 - \dfrac{\omega^2 m_1}{s_1'} + \dfrac{j\omega m_1}{Z_3}} . \tag{6}$$

The relationship between the force (acting) F_2' and the vibrational velocity of the surface v_1' can be directly expressed as follows:

$$F_2' = v_1' \cdot \frac{1}{\dfrac{j\omega}{s_1'} + \dfrac{1}{Z_3}} = \frac{F_1}{1 - \dfrac{\omega^2 m_1}{s_1'} + \dfrac{j\omega m_1}{Z_3}} . \tag{7}$$

From Eqs. (6) and (7), the ratio of the force of the tapping hammer F_1 to the input force for the concrete floor F_2' can be directly expressed as follows:

$$\frac{F_1}{F_2'} = 1 - \frac{\omega^2 m_1}{s_1'} + \frac{j\omega m_1}{Z_3} . \tag{8}$$

On the other hand, the vibrational energy transmission through a wood joist floor on the structural concrete slab is considered in the simulated model of an impact sound of floors for a wood joist shown in Fig. 4. Here, F_2 is the force (acting) of the wood floor, F_3 is the force from the wood joist into the structural concrete slab, F_1 is the force of the hammer, m_1 is the mass of the tapping machine hammer, v_1 is the vibrational verocity of the surface of wood floor, v_2 is the vibrational velocity of the concrete floor, v_3 is the vibrational velocity of wood joist, v_4 is the vibrational velocity of the structural concrete

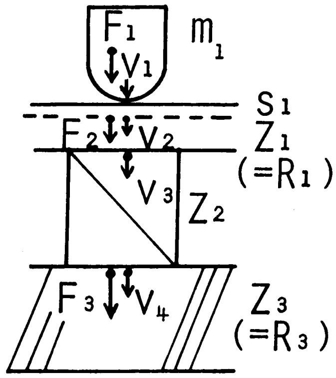

Fig. 4. A simulated model of the impact sound of floors for wood joist on the structural concrete slab.

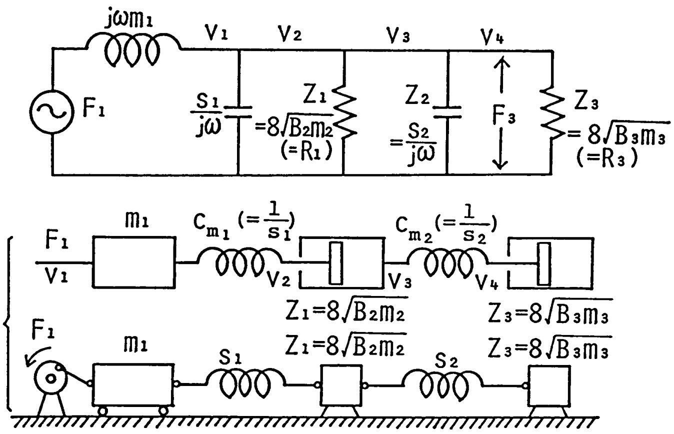

Fig. 5. An equivalent concentrated electric circuit model and an equivalent mechanical circuit model for the impact sound of a wood joist floor on the structural concrete slab.

slab, s_1 is the dynamic stiffness of the surface of the wood floor, Z_1 is the impedance of the wood floor, Z_2 is the impedance of the wood joist and Z_3 is the impedance of the structural concrete slab. When the tapping machine hammer drops on the wood floor above the air cavity between two joists, F_1 and v_1 are also calculated with an additional equivalent element. Figure 5 shows an equivalent electric circuit model as well as an equivalent mechanical circuit model for the impact noise transmission through a wood joist floor illustrated in Fig. 4 [8–10]. Thus, the velocity v_1 can be easily derived by the circuit calculation of the model in Fig. 5 as follows:

$$v_1 = \frac{F_1\left(\dfrac{j\omega}{s_1} + \dfrac{1}{Z_1} + \dfrac{1}{Z_2} + \dfrac{1}{Z_3}\right)}{1 - \dfrac{\omega^2 m_1}{s_1} + \dfrac{j\omega m_1}{Z_1} + \dfrac{j\omega m_1}{Z_2} + \dfrac{j\omega m_1}{Z_3}}. \tag{9}$$

Furthermore, the relationship between a force F_3 and the velocity v_1 can be easily expressed as follows:

$$\begin{aligned} F_3 &= v_1 \cdot \frac{1}{\dfrac{j\omega}{s_1} + \dfrac{1}{Z_1} + \dfrac{1}{Z_2} + \dfrac{1}{Z_3}} \\ &= \frac{F_1}{1 - \dfrac{\omega^2 m_1}{s_1} + \dfrac{j\omega m_1}{Z_1} + \dfrac{j\omega m_1}{Z_2} + \dfrac{j\omega m_1}{Z_3}} . \end{aligned} \tag{10}$$

From Eq. (10), the ratio of the force of hammer F_1 to the input force for the structural concrete slab F_3 is directly derived as follows:

$$\frac{F_1}{F_3} = 1 - \frac{\omega^2 m_1}{s_1} + \frac{j\omega m_1}{Z_1} + \frac{j\omega m_1}{Z_2} + \frac{j\omega m_1}{Z_3} . \tag{11}$$

Equation (8) corresponds to a special case of Eq. (11) when Z_1, $Z_2 \to \infty$, and s_1, F_3 become s_1', F_2', respectively. Also, this can be directly based on the above-mentioned equivalent circuits in Figs. 3 and 5. From Eqs. (8) and (11), the ratio of F_2' to F_3 can be obviously expressed as follows:

$$\frac{F_2'}{F_3} = \frac{1 - \dfrac{\omega^2 m_1}{s_1} + \dfrac{j\omega m_1}{Z_1} + \dfrac{j\omega m_1}{Z_2} + \dfrac{j\omega m_1}{Z_3}}{1 - \dfrac{\omega^2 m_1}{s_1'} + \dfrac{j\omega m_1}{Z_3}} . \tag{12}$$

The improvement of the impact noise reduction ΔL is given as the sound level difference in the room below between the impact sound level in the case of a bare concrete floor and the impact sound level in the case of the wood joist floor on the structural concrete slab. More specifically, ΔL can be expressed as follows:

$$\begin{aligned} \Delta L &= 10 \log \left| \frac{F_2'}{F_3} \right|^2 \\ &= 10 \log \left| 1 - \frac{\omega^2 m_1}{s_1} + \frac{j\omega m_1}{Z_1} + \frac{j\omega m_1}{Z_2} + \frac{j\omega m_1}{Z_3} \right|^2 \\ &\quad -10 \log \left| 1 - \frac{\omega^2 m_1}{s_1'} + \frac{j\omega m_1}{Z_3} \right|^2 . \end{aligned} \tag{13}$$

Such a circuit-theoretical consideration seems to be at the early stage of study in this field. So, for the purpose of emphasizing only some principle aspects, let us consider a standard case when the impedance of the wood joist Z_2 is given only by the dynamic stiffness, and the impedance of the wood floor Z_1 and also the impedance of the structural concrete floor Z_3 are nearly equal to the driving point impedance of infinite panel, respectively. That is, $Z_2 = s_2/j\omega$ for the wood joist, $Z_1 = 8\sqrt{B_2 m_2}$ for the wood floor and $Z_3 = 8\sqrt{B_3 m_3}$ for the structural concrete floor, where s_2 denotes the dynamic stiffness of the wood joist, B_2 and B_3 denote the bending stiffness of the wood floor and the structure concrete floor, m_2 and m_3 denote the surface mass per unit area of the wood floor and the structural concrete floor, respectively. When the upper wood floor plate and the lower structural concrete slab are considered to be isotropic and homogeneous, ΔL is derived from the above background, as follows:

$$\begin{aligned}\Delta L &= 10\log\left|1-\frac{\omega^2 m_1}{s_1}-\frac{\omega^2 m_1}{s_2}+\frac{j\omega m_1}{8\sqrt{B_2 m_2}}+\frac{j\omega m_1}{8\sqrt{B_3 m_3}}\right|^2\\ &\quad -10\log\left|1-\frac{\omega^2 m_1}{s_1'}+\frac{j\omega m_1}{8\sqrt{B_3 m_3}}\right|^2. \end{aligned}\tag{14}$$

In the case of using a resilient material under the wood joist, the total stiffness is given by a summation of each stiffness. That is, it can be expressed by a parallel circuit of condenser in an equivalent electric circuit. Accordingly, we directly have

$$\frac{1}{s_T}=\frac{1}{s_2}+\frac{1}{s_m}\,, \tag{15}$$

where s_T denotes the total stiffness of a wood joist and the resilient material, and s_m denotes the stiffness of the resilient material. This shows an improvement of the impact noise reduction for the resonantly reacting floating floor system [11, 12].

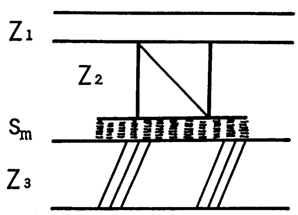

Fig. 6. A simulated model of the wood joist floor using a resilient material under the wood joist.

Here, we have to point out that all of such equivalent electric circuit models employed are based on the well-known standard Force-Voltage equivalent method and so the velocity change between input and output sites means in principle to produce a parallel type of the electric circuit of the model [13].

3. Experimental considerations

The improvements of an impact noise reduction for a wood joist floor on the structural concrete slab for the excitation by an I.S.O. standard tapping machine, were measured in house. Figures 7 and 8 show a comparison between the theoretically predicted values and the experimentally sampled points for the impact noise reduction ΔL (dB) in the room below when the plywood floor plate thickness is 13 mm and the concrete slab thickness is 120 mm. In Fig. 7, the impact noise reduction of the wood joist floors is illustrated theoretically and also experimentally in the case with the 45 mm $\times$ 50 mm wood joist (300 mm interval) on the structural concrete slab, where the stiffness of wood joist s_2 is

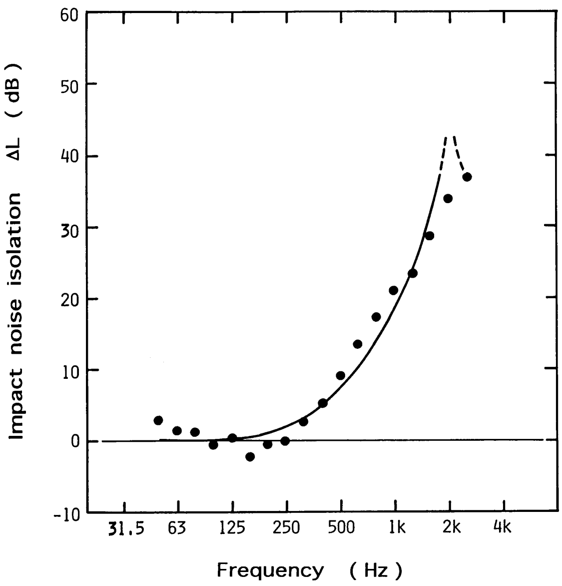

Fig. 7. A comparison between the theoretically predicted values and the experimentally sampled points for the impact noise reduction of a wood joist floor on the concrete floor slab.

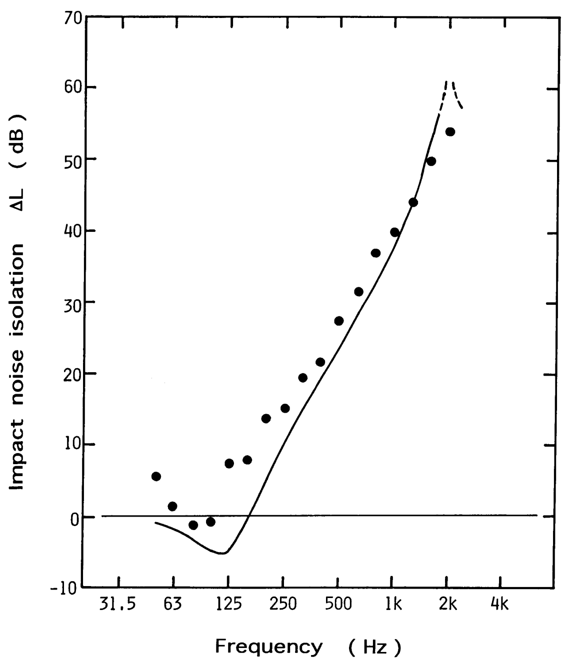

Fig. 8. A comparison between the theoretically predicted values and the experimentally sampled points for the impact noise reduction of a wood joist floor using a resilient material under the wood joist.

estimated at 3.4×10^6 N/m. In Fig. 8, the theoretical curve for the impact noise reduction of the wood joist floor agrees satisfactorily with the experimentally sampled points in the case of the 45 mm × 50 mm wood joist (300 mm interval) with a resilient material (25 mm thick fiberglass; 96 kg/m^3) on the structural concrete slab, where the total stiffness of wood joist s_T is estimated at 3.2×10^5 N/m. In the case of a resilient material, the negative improvement can be observed in the vicinity of the resonance frequency caused by the total stiffness of the wood joist with a resilient material under the joist. It can be obviously recognized that all of the theoretical values achieve a fairly good agreement with the experimental results.

4. Conclusions

A new theoretical and fundamental study on the impact sound of floor is proposed in the case of a wood joist floor on the structural concrete slab for the purpose of reducing the impact sound level in the lower room in the house. Especially, this trial is based on an equivalent lumped constant type electric circuit model as well as on an equivalent mechanical circuit model for the impact noise transmission of the wood joist floor. It has been designed in principle for the daily life sound environment. Thus, a practical evaluation of the impact noise reduction can be theoretically estimated by the method proposed in Eqs. (13) or (14). In the case of a wood joist floor using a resilient material under the wood joist, the theoretical values of the impact noise reduction have also been successfully predicted by Eq. (14). This case is a kind of resonantly reacting floating floor system. It is obviously shown that all of the theoretical values show a good agreement with the experimental results. And, the effectiveness of the method proposed from a circuit-theoretical viewpoint has been experimentally confirmed with several types of actual applications for the excitation by a standard tapping machine.

As one can understand, such a theoretical consideration based in this paper on two types of equivalent electric and mechanical circuit models is obviously at an early stage of study, and so its experimental consideration remains only in the principle confirmation of the proposed theory. Up to date, this theory can be used on a few conditions: 1) the most of the elements are smaller than wave lengths, 2) the size of the floor is infinitely large compared with other elements, 3) there is no other circuit-theoretical interaction between joists. Accordingly, a piece of research is needed to find minute modification methods under the introduction of more detailed circuit models (e.g., distributed constant type equivalent circuit model) and to apply them to more actually complicated house systems (e.g., location of a driving point, some modification for a case of finite panel, and so on).

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