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Experimental approach on transmission of low-frequency sound into a building

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ABSTRACT

Field experiments were conducted to investigate transmission of low-frequency sound into a test building by using a transportable device that could generate low frequency sounds down to 2 Hz. Results show no significant inside-outside SPL differences at 4 Hz or lower. Theoretical analysis indicated that this tendency is affected by the air-tightness of the test building. For higher frequency regions around 12.5 Hz, it was inferred that the vibration of the windows play an important role on the SPL difference between outdoors and indoors. In addition, SPL increase due to the presence of a building with glass panes was investigated. Below 10 Hz, the SPL difference in front of the building was less than 2 dB. However, above 20 Hz, the SPL in front of the building increased up to 6 dB when the building existed.

Keywords: low-frequency sound, field experiment, insulation
I-INCE Classification of Subjects Number(s): 21.8.1, 51.4

1. INTRODUCTION

Since "LFS (Low Frequency Sound)" was added to the contents of environmental assessment, LFS has recently been more frequently estimated in Japan. Low-frequency and/or G-weighted SPL (sound pressure level) at the outdoor evaluation points are estimated based on attenuation characteristics with the distance from the source and/or measured data of similar cases of the past. On the other hand, in order to estimate human feeling and window rattling indoors, it is necessary to understand sound insulation characteristics.

Shimizu et al (1) reported results for measuring SPL differences 1 m in front of and behind the windows. Ochiai et al (2) measured SPL differences for aircraft noise and wind turbine noise's low frequency components, at one point indoors and one point outdoors between 3-10 m away from the building. Since these data were measured at one point both inside and outside, influences on measured values outdoors due to sound reflected from the building and distribution conditions for LFS indoors are not clear. One of the reasons is the difficulty of generating LFS that restrict experimental investigation. The authors developed an experimental device that generates LFS with frequency ranging from 2 to 100 Hz (3), and measured insulation of actual buildings against LFS by using this device (4). Results showed that the indoor-outdoor SPL difference in the frequency range below 100 Hz varied significantly according to frequency, room size, air-tightness of gaps, natural frequency of the windows, and so on. On the other hand, theoretical approach regarding insulation characteristics and experimental approach regarding influences on SPL in front of buildings by the presence of the buildings have not been conducted yet. In this paper, we conducted field experiments by using a test building and the LFS device, and discussed measured insulation characteristics and their possible causes from both theoretical and experimental points of view.

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2. Procedure of Measurement

2.1 Sound Source

The LFS source shown in Fig.1 was used in the field experiment. A pair of aluminum honeycomb boards with the dimensions of 1 m x 1 m vibrated in opposite phases by the use of a pneumatic servo actuator powered by compressed air. The sound source behaves like a pulsating sphere in low frequency range. The vibrating plates are surrounded by an enclosure with 26 m^3 of volume, which acts as a speaker box for reducing the pressure variation inside the box. The maximum stroke of the vibrating board is 140 mm (peak to peak). Table 1 shows the specifications of the sound source. This source could generate LFS with a frequency range between 2 and 100 Hz. The maximum SPL at 3 m from the sound source is over 110 dB (5-20 Hz).

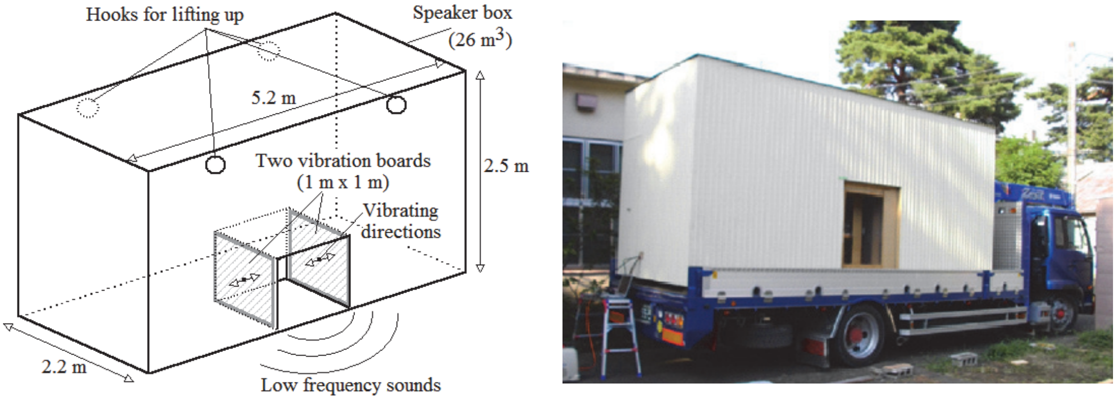

Figure 1 – Outline of low frequency sound source

Table 1 – Specifications of the low frequency sound source

Driving method	Pneumatic servomechanism
Control method	Displacement feedback
Vibrating board	Honeycombed aluminum board (2 pieces), size=1m x 1m
Driving frequency	2 - 100 Hz
Power	110 dB at 3m (5 - 20 Hz)
Piston stroke	Maximum ±70 mm

2.2 Test Building

Field experiments were conducted to investigate sound transmission characteristics of a test building. This test building has a typical wooden Japanese construction and its dimensions are 5.1 m wide x 2.1 m deep x 2.5 m high. Horizontally sliding glass doors surrounded by an aluminum frame of 1.6 m wide x 1.8 m high are attached to one of the walls. The thickness of the glass panes is 5 mm. A metal door is installed on another side of the test building, as shown in Fig.2.

Figure 2 – Test building

2.3 Field Experiment

Figure 3 shows the arrangement of the sound source, measuring position and the test building. Indoor and outdoor sound pressure was measured by using low-frequency microphones (RION XN-12A : 0.2 Hz – 1 kHz; GRAS 40AZ-S1: 0.09 Hz – 20 kHz). The intervals of the outdoor microphones are 1 m. The heights of the microphones are 0.5m. The displacement of the glass doors was also measured by using a laser displacement gauge (KEYENCE LK-G155).

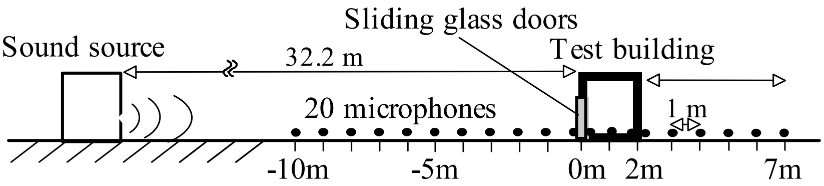

Figure 3 – Arrangement of the sound source, measuring position and the test building

3. RESULTS

3.1 SPL Inside and Outside the Test Building

Figure 4 shows examples of the experimental results for the frequencies of 4 and 10 Hz. There is a tendency that SPL decreases with distance from the source at -6 dB/DD, the rate for the spherically spreading waves. The influences of the presence of the building can be more clearly observed by offsetting the tendency of distance attenuation as shown in the graphs on the right-hand side of Fig. 4. It is found that the indoor (0 – 2 m) sound is smaller than outdoor sound at 10 Hz. Figure 5 shows SPL after offsetting the tendency of distance attenuation in the frequency range 4 -100 Hz.

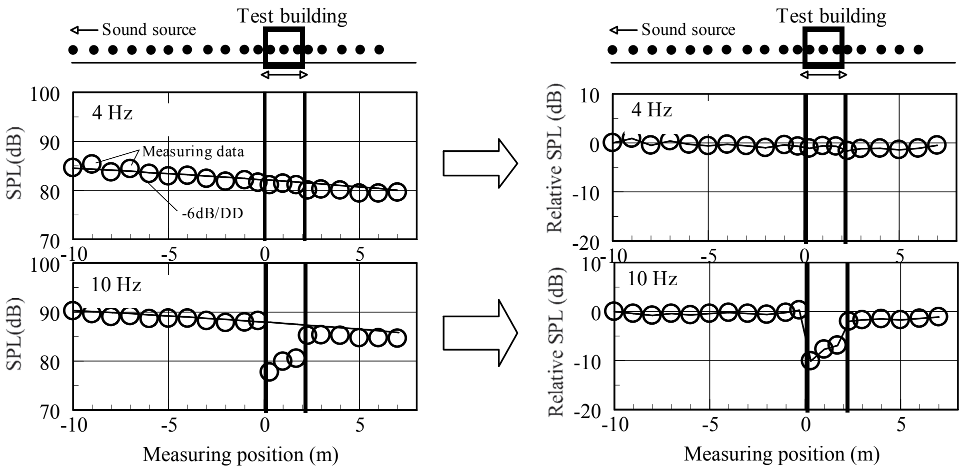

Figure 4 – Examples of experimental results on SPL distributions inside and outside the test building

From the results shown in Fig. 5, even for LFS, it is found that indoor and outdoor SPL were affected by the presence of the test building. Figure 6 indicates indoor-outdoor SPL differences calculated by using data shown in Fig. 5. In this calculation, the average SPL at 3 indoor points was used as the indoor value, and SPL right outside of the building as the outdoor value. From Fig. 6, it is found that indoor-outdoor SPL difference depends on frequency. SPL difference for frequency lower than 5 Hz and around 12.5 Hz was especially small. It is inferred that the small indoor-outdoor SPL difference for frequency below 5 Hz is mainly due to the air-tightness of the room, and SPL difference for frequency around 12.5 Hz is mainly due to the natural frequency of the windows. These two factors on indoor-outdoor SPL difference are discussed in Sec. 3.2 and 3.3, respectively. Effects of the presence of the building are also considered in Sec. 3.4.

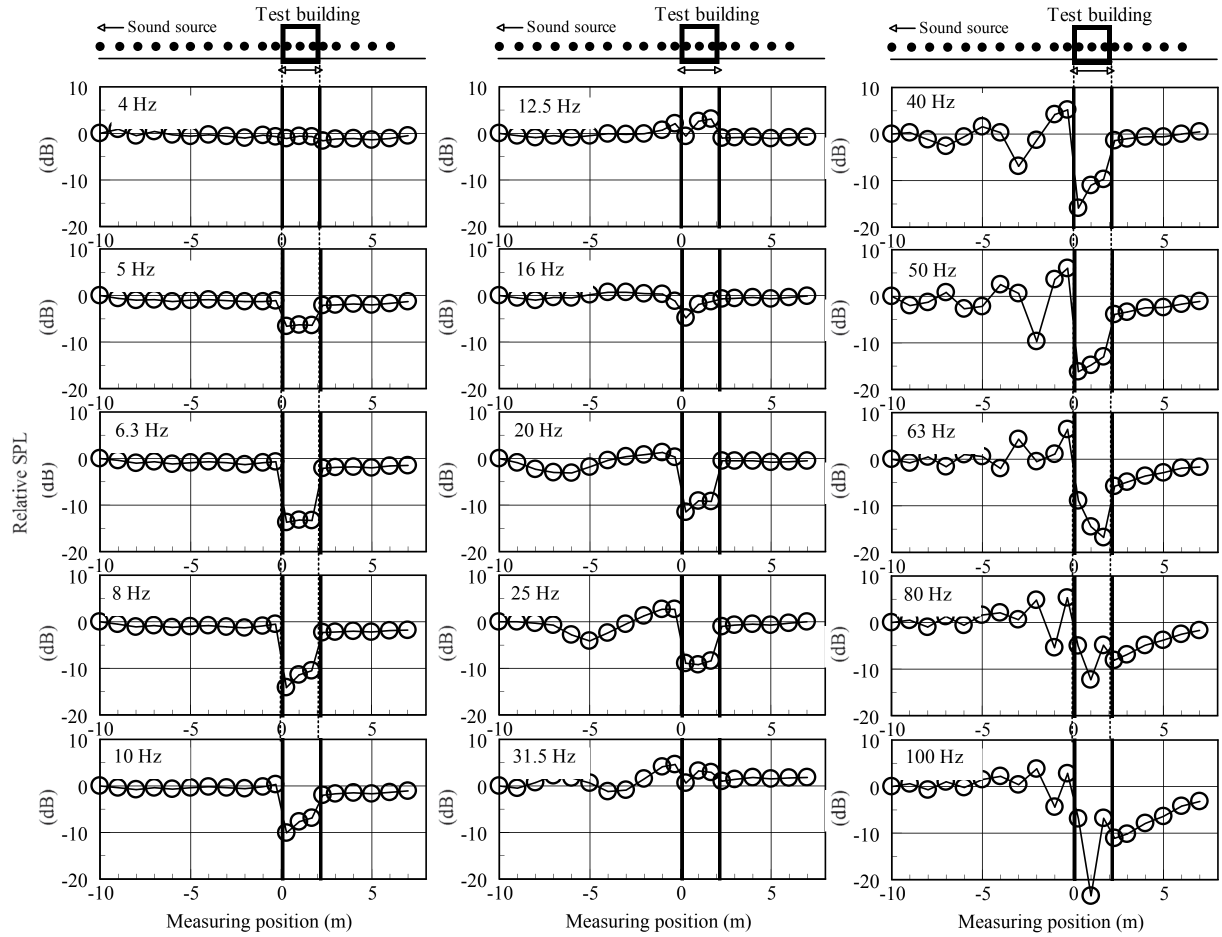

Figure 5 – Experimental results on SPL distributions inside and outside the test building after removing a tendency of distance attenuation

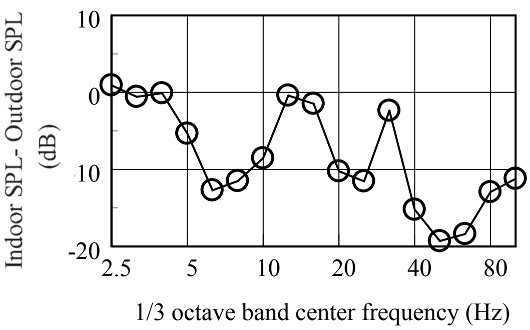

Figure 6 – Indoor-outdoor SPL differences (measured results)

3.2 Indoor–Outdoor SPL Differences under 10 Hz (Influence of Air-Tightness)

In the previous study (4), it was found that air-tightness due to gaps of doors and windows affect indoor-outdoor SPL difference at 10 Hz and lower. In this study, we attempt to explain the effects of air-tightness on indoor-outdoor SPL differences by using a theoretical model.

3.2.1 Theoretical Model

We assume that air pressure P and air volume V obey the ideal gas law of $P(t)V(t)=nRT$ and that the temperature T remains constant (isothermal process). Therefore, for a certain amout of substance of gas, i.e. for a fixed value of n, $P(t)V(t)$ is constant. Air flows indoors and outdoors through the gaps of the doors at the flow rate of $Q(t)$. (See Fig. 7(a).) $Q(t)$ is assumed to be proportional to the pressure difference between indoors and outdoors and expressed as follows:

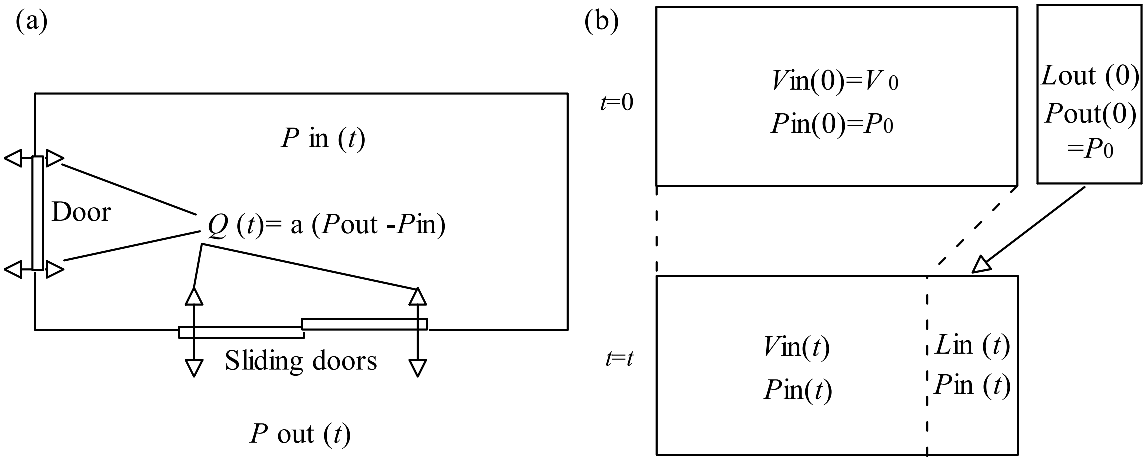

Figure 7 – Theoretical model including influence of the air-tightness,
(a):relationship between flow and pressure difference,
(b):relationship between air volume of the room and the volume of air flowing in the room

$$Q(t) = a(P\text{out}(t) - P\text{in}(t)) \qquad (1),$$

where $P\text{out}(t)$ is outdoor pressure and $P\text{in}(t)$ is indoor pressure. Note that $P\text{out}(t)$ and $P\text{in}(t)$ are absolute pressure and not acoustic pressure.

The air volume depends on the pressure, and so does the flow rate. In this study, $Q(t)$ is defined as the flow rate under the condition of the ambient atmospheric pressure P_0. Therefore, from Eq. (1), the volume $L\text{out}(t)$ of air flowing into (or out of) the room under the pressure condition of P_0 can be written as Eq.(2).

$$\begin{aligned} L\text{out}(t) &= \int^t Q(\tau)d\tau \\ &= \int^t a(P\text{out}(\tau) - P\text{in}(\tau))d\tau \end{aligned} \qquad (2),$$

where a is a content of proportional.

When air flows into the building, the volume of air originally resided inside the building ($V\text{in}$) and the volume of air flowed into the building ($L\text{out}$) changes as illustrated in Fig. 7 (b). On these volumes, the following relationships are obtained from the isothermal assumption:

$$P\text{in}(t)V\text{in}(t) = P_0 V_0 \qquad (3),$$

$$P\text{in}(t)L\text{in}(t) = P_0 L\text{out}(t) \qquad (4),$$

in which V_0 is the inner volume of the building. $V_0(=V\text{in}(0))$ is the sum of $V\text{in}(t)$ and $L\text{in}(t)$ as shown in Fig.7(b). Therefore, V_0 is expressed as

$$V_0 = V\text{in}(t) + L\text{in}(t) \qquad (5).$$

Eliminating $V\text{in}(t)$, $L\text{in}(t)$, and $L\text{out}(t)$ from Eqs. (2) – (5) and taking the derivative with respect to t yields the following differential equation:

$$\frac{dP\text{in}(t)}{dt} = \frac{P_0}{V_0} a(P\text{out}(t) - P\text{in}(t)) \qquad (6).$$

For given *P*out, the time histories of *P*in can be calculated from Eq. (6) in a time-marching manner. As a result, SPL difference between indoors and outdoors is obtained from *P*in and *P*out.

3.2.2 Theoretical Results

The indoor-outdoor SPL difference was calculated according to the theoretical model above for three different air-tightness conditions and is plotted in Fig. 8. The values of the proportional coefficient *a* for the air flow rate *Q*(*t*) in Eq. (1), which represent the air-tightness condition, are set at 0.006m^3/s/Pa (Case1), 0.003m^3/s/Pa (Case2) and 0.0015m^3/s/Pa (Case3). Case3 is the highest air-tight condition.

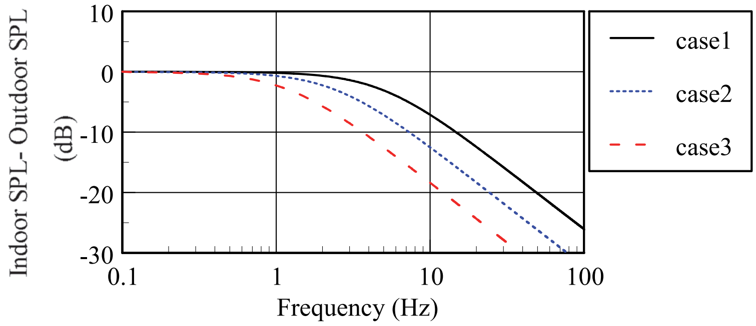

Figure 8 – Theoretical results on indoor–outdoor SPL differences

In this figure, there is a tendency that indoor-outdoor SPL difference decreases as frequency decreases. Below 2 Hz, indoor-outdoor SPL difference is smaller than 5 dB. In addition, there is a tendency that indoor-outdoor SPL difference increases as air-tightness increases. In this theoretical model, we assumed that indoor pressure *P*in is uniform. In the previous study (5), it was found that SPL distribution indoors is uniform below 10 Hz. Therefore, theoretical results were plotted only up to 10 Hz in Fig. 9.

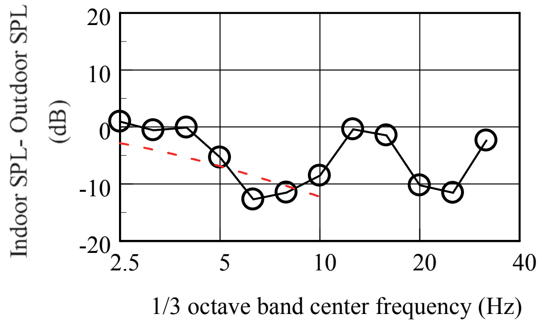

Figure 9 – Theoretical and experimental results on indoor-outdoor SPL differences
(black circles : experimental, red dashed line : theoretical)

Below 8 Hz, both theoretical and experimental results indicate the same tendency that indoor-outdoor SPL difference decreases as the frequency decreases. Theoretical and experimental results did not match quantitatively, but they matched qualitatively. In the future, we plan to measure air-tightness of buildings, and to compare experimental results with calculated results. Furthermore, we would like to take window vibration into consideration in the theoretical model, in addition to air-tightness.

3.3 Indoor–Outdoor SPL Difference around 12.5 Hz (Influence of Natural Frequency of Glass Doors)

Next, to understand indoor-outdoor SPL difference around 12.5 Hz, we focused on the natural frequency of the doors. Figure 10 shows the relationship between outdoor sound and sliding glass door displacement. From this figure, it is found that the doors have the largest vibration displacement at 12.5 Hz. Therefore this frequency is assumed to be the natural frequency.

Figure 11 shows the displacement response of the door when exposed to an impulsive sound with time duration of 1 ms (5). This experimental result also supports that the doors vibrate in natural frequency at 12.5 Hz.

Therefore, the reason why indoor-outdoor SPL difference around 12.5 Hz is small seems to be due to the natural frequency of the doors. In the future, we would like to theoretically discuss the natural frequency of doors.

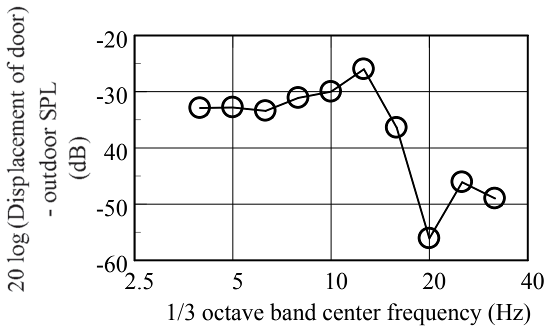

Figure 10 – Measured results on relationship between outdoor sound and door displacement

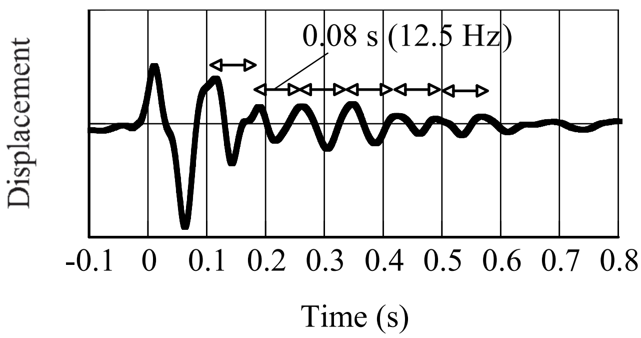

Figure 11 – Measured results on impulse responses of door displacement

3.4 SPL in Front of Building over 20 Hz (Influence of Reflected Sound from Glass Panes)

The indoor-outdoor SPL difference shown in Fig. 6 is calculated by using SPL right outside of the building. However, SPL in front of the building may be affected by the presence of the building and SPL may increase. Therefore, we now discuss SPL increase due to the presence of a building. Figure 12 shows the effect of the building on SPL at 0.1 m and 1 m away from the glass panes. These data indicate that SPL change due to the presence of the building, i.e., the variation from zero in Fig. 5.

No significant SPL increase due to a building is found below 20 Hz because the wavelength is much longer than the width of test building (5 m). On the other hand, in the 25-50 Hz range in which the wavelength is about twice the width of test building, SPL increase gets larger as frequency increases. The maximum SPL increase measured at 0.1 m is about 6 dB at 50 Hz. Therefore, this SPL increase is thought to be caused by sound reflected from the glass panes. SPL measured at 1 m tends to decrease with frequency due to standing waves (80 Hz). Therefore, it is necessary to take into consideration these influences when measuring SPL in front of the building. In addition, in the previous study, there is an example of experimental results indicating that the effect of the reflected sound can be small at 5 m away from the side of building (6). Thus, measurements at such a location could be a good reference.

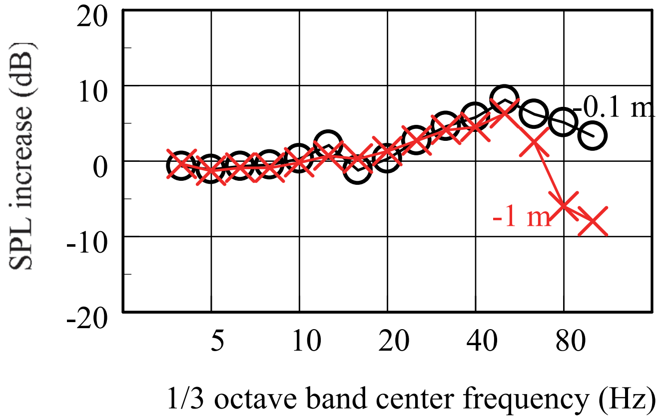

Figure 12 – Measured results on SPL increase due to the presence of a building (in front of the building, 0.1 m and 1 m away from the glass panes)

4. CONCLUSIONS

Field experiments were conducted to investigate transmission of low-frequency sound into a test building. Results showed no significant inside-outside SPL difference at 4 Hz or lower. Theoretical analysis indicated that this tendency is affected by the air-tightness of the test building. It was also found that window vibration plays an important role on the transmission of LFS at frequencies near the natural frequency of the window. In addition, SPL increase due to the presence of a building with glass panes was investigated. It was found that taking SPL increase due to the presence of the building into consideration is necessary to measure indoor-outdoor SPL difference for actual buildings, as the pressure distribution around buildings is not uniform.

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