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Loudness of structure borne sound heard directly by ear put on vibrating structure

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Summary

Putting an ear close to a vibrating structure like a wall or a floor, we are able to hear structure-borne sounds clearly, but the loudness of such sounds has never been studied quantitatively. In this study, subjective experiments were carried out in order to obtain the relationship between loudness and the vibration amplitude of the ear's contact surface at low audible frequencies. The main result of this study is that the loudness of a structure-borne sound is almost equal to that of an air-borne sound with a sound pressure level 20 dB higher than the vibration velocity level (ref=5×10^{-8} m/s) of the surface. According to this result, the loudness of the structure-borne sound heard directly can be evaluated as a sound pressure level derived from the measured vibration amplitude of the structure.

Introduction

We usually hear a structure-borne sound or transmitted sound through a wall after it has radiated from vibrating structures into rooms or outdoor. And we know by experience that a structure-borne sound can be heard more clearly by someone who puts his/her ear close to the vibrating structure. This is done, for example, when one tries to judge if the outer walls of a building emit any noise, or to find out what the strange sound coming from the next room through the wall really is. In these cases, we make use of the phenomenon that the loudness of a structure-borne sound becomes stronger when we put our ear on the vibrating surface.

On the other hand, this phenomenon can have negative effects. In an actual case, a complaint against a diesel plant had been made from a neighbour complaining that the diesel's noise was heard from the floor of the apartment house when he was lying down on it. As a result of researches, it came out that the ground vibration travelled from the plant to the apartment house and that the resident heard structural vibration in the audio frequency range as a structure-borne sound directly from the floorboard. In this case, such a diesel's noise from the floorboard could not be evaluated numerically because the loudness of such structure-borne sounds had never been quantitatively studied before.

The purpose of this study is to obtain the relationship between loudness and the vibration amplitude of ear's contact surface at low audible frequencies by carrying out subjective experiments.

Method

For these experiments, we used the method of adjustment. The subjects hear the structure-borne sound and the air-borne sound alternatively and adjust the volume of the air-borne sound to the same magnitude as that of the structure-borne sound. The sound pressure level of the air-borne sound having been adjusted is defined for convenience as an "equivalent structure-borne sound pressure level (ESBSPL)". The measured ESBSPL is compared with the vibration velocity level (ref=5×10^{-8} m/s) of the ear's contact surface.

In order to examine the damping effect of bedding, additional tests were also performed in which a pillow was inserted between the vibrating surface and the subjects' ear.

Subjects. Both ears of 5 subjects (i.e. 10 ears) were tested, the subjects of both sexes having normal hearing and an age ranging from 27 to 52.

Signals. Test signals are pure tones at center frequencies of the third octave bands of 50 Hz to 160 Hz inclusive.

Generators. The structure-borne sound generator was prepared especially for these experiments. It includes a piece of a board called the “vibrant-board”, which is in contact with the subject’s ear. The vibrant-board is fixed on a covering board of the specific loudspeaker as shown in Fig. 1. Vibrational energy of the covering board caused by sound pressure generated by the loudspeaker propagates to the vibrant-board and subjects can hear it as a structure-borne sound. The vibration amplitude of the vibrant-board is measured by an accelerometer attached to its back surface. Undesirable sound radiation from the covering board is dumped by glass wool and rubber sheets placed on it.

Another loudspeaker was installed in the examination room to generate the air-borne sound used for the comparison with the structure-borne sound.

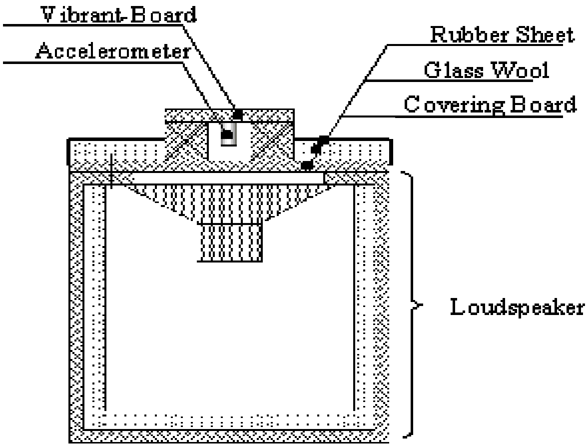

Figure 1. The structure-borne sound generator especially prepared for these experiments.

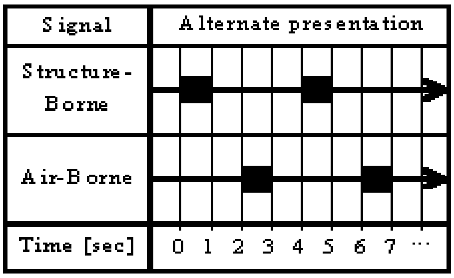

Figure 2. Alternate presentation of the structure-borne signal and of the air-borne signal.

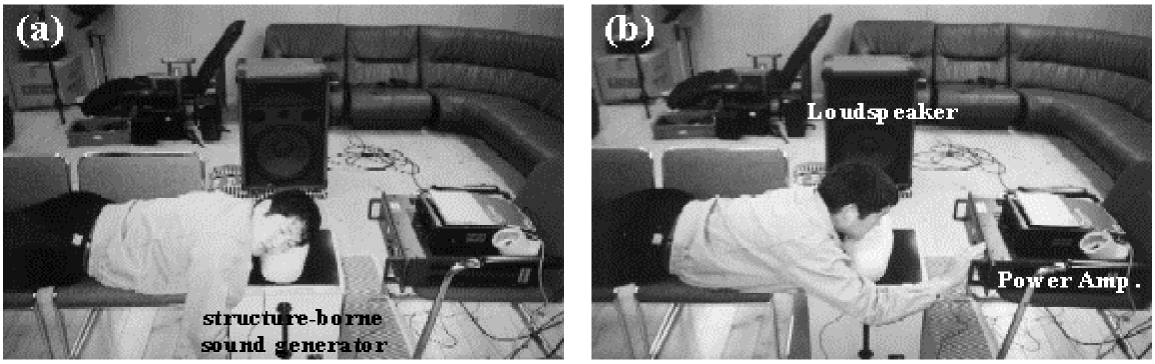

Figure 3. Pictures of the experiments. A subject is hearing the structure-borne sound with its left ear through the pillow (a) and adjusting the air-borne sound from the loudspeaker (b).

Procedure. Test signals were sent to the subjects alternatively from the structure-borne sound generator and from the loudspeaker (air-borne sound generator) with a time interval as shown in Fig. 2. In the experiment, a series of repeating sounds is sent in which each subject hears the structure-borne sound while putting one of his/her ears on the vibrant-board, and then hears the air-borne sound while taking that ear off the board. Pictures of the experiments are shown in Fig. 3. The non-tested ear of the subject is occluded with an earplug. During a test, the input voltage to the loudspeaker is adjustable while that of the structure-borne sound generator is fixed. Each subject must adjust the sound volume of the loudspeaker until he/she judges that the tone heard from the loudspeaker has the same magnitude as that of the tone heard from the vibrant-board. Once the adjustment is done, the sound pressure level of the loudspeaker's tone at the point where the subject's ear is located and the vibration velocity level of the vibrant-board are measured.

Results

Experimental results are shown in Fig. 4. Measured values of ESBSPL and vibration velocity level were each averaged among subjects at each frequency. It can be seen that the average values of ESBSPL are about 20 dB (18 to 21 dB) higher than those of vibration velocity level, and these level differences have little dependence on frequency. Differences in the particular values of ESBSPL among subjects, also shown in Fig. 4 are rather large, especially at frequencies lower than 80 Hz, where they spread over more than 10 dB. In contrast, differences in the particular values of vibration velocity level among subjects caused by differences of ears pressure -not shown in the Figures- were small, and less than 1 dB at frequencies below 125 Hz and 4 dB at 160 Hz.

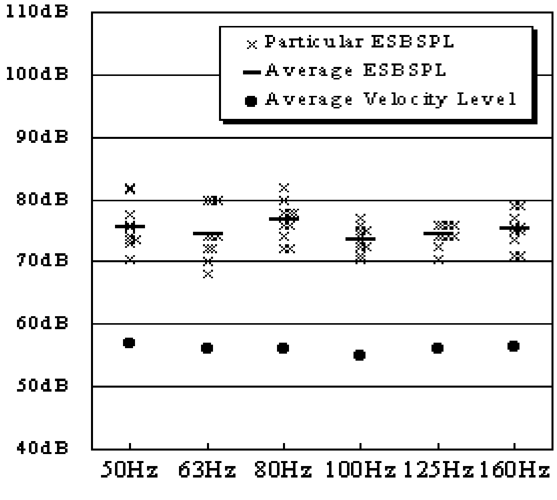

Figure 4. Experimental results of ESBSPL and vibration velocity level of the vibrant-board.

Results of the additional tests using a pillow are shown in Fig. 5. It can be seen that the average values of ESBSPL measured using a pillow become smaller, and differences among subjects become larger than those in Fig. 4. Damping effects of the pillow in average ESBSPL are 9 dB to 14 dB as shown in Fig. 6, and these effects tend to increase with an increase in the frequency except at 160 Hz.

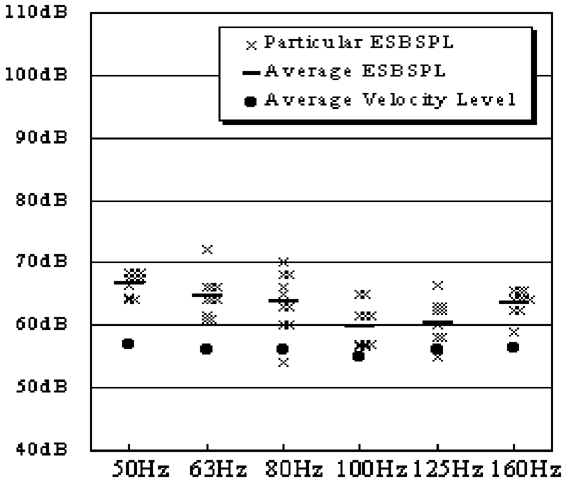

Figure 5. Results of additional tests using the pillow containing buckwheat chaff.

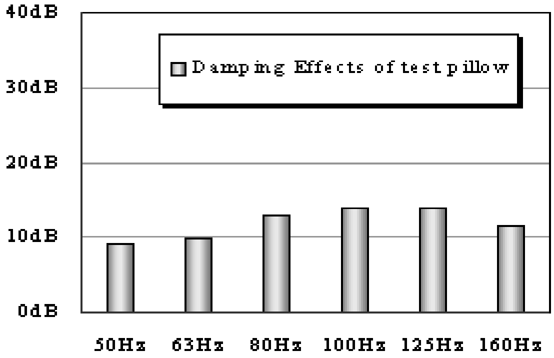

Figure 6. Damping effects of the pillow on average ESBSPL.

Amplification in the ear cavity

It is known that the sound power level (ref=10^{-12} W) per m^2 of a vibrating plane surface has the same value as the vibration velocity level of the surface if the radiation efficiency is unity, and that the sound pressure level immediately in front of the surface is approximately equal to the vibration velocity level in a open space. Furthermore, in practice, radiation efficiency becomes considerably smaller at low frequencies and consequently the sound pressure level becomes less than the vibration velocity level. In contrast, experimental results show an ESBSPL 20 dB higher than the vibration velocity level. We believe that such a large difference between sound pressure level and ESBSPL may be caused by amplification of sound pressure in the ear owing to ear's occlusion by the vibrant-board. In order to have a good description of the conditions of amplification in the closed space of the ear cavity, an analysis of occlusion effects has been performed using the simple model described below.

The analysis model consists in a vibrating surface, the opening of the ear cavity and a small gap between the surface and the ear as shown in Fig. 7. The ear's opening has a circular shape of 25mm in diameter which is equal to a IEC artificial ear [1], and measured acoustic impedance of human ears Z_A (Tab. 1) are given for the opening. The area of the opening is S and that of the gap is given by δS, *where* δ is the ratio of the gap area to that of the opening. A specific acoustic impedance ρc is given to the boundary of the gap, where ρ is density of air and c is the sound speed in air. Considering the balance of volume velocities,

$$Sv=p/Z_A+\delta Sp/\rho c \qquad (1)$$

where v is the vibration velocity of the surface and p is the sound pressure of the ear cavity. The distribution of pressure is neglected because at low frequencies, the ratio of the cavity

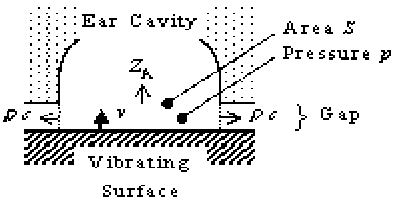

Figure 7. Analysis model of the ear cavity and of the vibrating surface.

Table 1. Acoustic impedance Z_A of human ears (measured by M.E.Delany).

Hz		25	31.5	40	50	63	80	100	125	160
Z_A	Re	3.8	3.0	2.3	1.8	1.5	1.3	1.1	1.0	0.9
	Im	-9.6	-9.1	-8.6	-8.0	-7.2	-6.2	-5.0	-3.8	-2.0

$\times 10^7$ [N sm^{-5}]

dimensions to the wavelength is small. The left side of eq. (1) represents the volume velocity caused by a portion of the vibrating surface adjacent to the ear cavity. The right side of eq. (1) is the sum of the volume velocities reaching the ear cavity and the gap. Rearranging terms, the level difference ΔL between the sound pressure level L_p and the vibration velocity level L_v is given by

$$\Delta L = L_p - L_v = 20\log_{10}(v_0/p_0) - 20\log_{10}(1/SZ_A + \delta/\rho c) \qquad (2)$$

where v_0 is the reference velocity of 5×10^{-8} m/s and p_0 is the reference pressure of 20 μPa.

Calculations of frequency characteristics of ΔL for different δ are shown in Fig. 8. When there is no gap (δ=0%), ΔL is very large especially at lower frequencies where it is larger than 40 dB. When the gap increases, ΔL begins to fall immediately and the frequency characteristics become rather flat. ΔL is about 20 dB for δ= 10% which is close to the experimental result. In this model, an area ratio δ of 10% is equivalent to an even gap of 0.6 mm in width. It seems therefore that sound leakage from such gaps naturally formed between subject's ear and the vibrant-board caused large differences in ESB SPL observed among subjects.

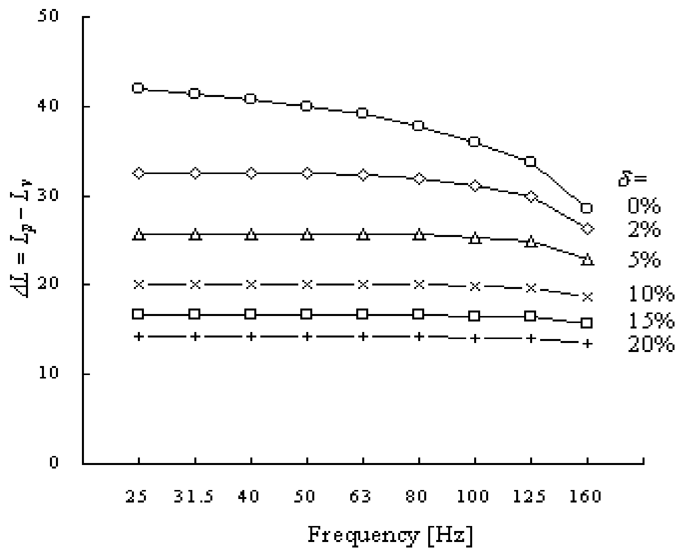

Figure 8. Frequency characteristics of calculated level difference $\Delta L = L_p - L_v$ for different ratios δ.

Practical application

Based on these experimental results, we can evaluate the magnitude of the foregoing diesel's noise heard directly from the floorboard of the apartment house. Table 2 shows a procedure to convert the vibration acceleration level (ref=10^{-6} m/s^2) of the floorboard into A-weighted ESBSPL, which can be evaluated in the same way as A-weighted sound pressure level of ordinary air-borne noise. The loudness of the diesel's noise will be about 47 dB(A) if one hears it with the ear put on the floor, and it will decrease to about 37 dB(A) by using a bedding like a pillow. Another option would be to treat it as a structure-borne low frequency noise and to evaluate its non-weighted ESBSPL in the same way as air-borne low frequency noise.

Table 2. Conversion from vibration acceleration level to A-weighted ESBSPL.

Frequency [Hz]	OA	50	63	80	100	125	160
Vibration Acceleration Level	78	58	72	73	74	60	60
Conversion to Velocity Level	–	–24	–26	–28	–30	–32	–34
Vibration Velocity Level	50	34	46	45	44	28	26
Conversion to ESBSPL	–	19	18	21	19	18	19
ESBSPL	69	52	64	65	62	47	45
A-weighting	–	–30	–26	–23	–19	–16	–13
A-weighted ESBSPL	47	22	38	43	43	30	31

Conclusions

Results of subjective experiments show that the structure-borne sound which one hears with one's ear resting on a vibrating surface is as loud as an air-borne sound whose pressure level is about 20 dB higher than the velocity level of the surface, and it decreases by about 10 dB by using a pillow. Based on these results, we are able to evaluate the loudness of the structure-borne sound as what is heard from a floor when lying down on it.

References

[1]IEC 60318-1 (1998-07) Electroacoustics - Simulators of human head and ear - Part 1: Ear simulator for the calibration of supra-aural earphones

[2]M.E.Delany:The acoustical impedance of human ears. J.Sound.Vib.1,pp.455-467 (1964)