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Definition and measurement of sound energy level of a transient sound source

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Concerning stationary sound sources, sound power level which describes the sound power radiated by a sound source is clearly defined. For its measuring methods, the sound pressure methods using free field, hemi-free field and diffuse field have been established, and they have been standardized in the international and national standards. Further, the method of sound power measurement using the sound intensity technique has become popular. On the other hand, concerning transient sound sources such as impulsive and intermittent sound sources, the way of describing and measuring their acoustic outputs has not been established. In this paper, therefore, "sound energy level" which represents the total sound energy radiated by a single event of a transient sound source is first defined as contrasted with the sound power level. Subsequently, its measuring methods by two kinds of sound pressure method and sound intensity method are investigated theoretically and experimentally on referring to the methods of sound power level measurement.

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1. INTRODUCTION

In noise control problems, it is essential to obtain the information regarding the noise sources. Concerning stationary sound sources, "sound power level" which describes the sound power (sound energy per 1 s) radiated by a sound source is clearly defined. For its measuring methods, the sound pressure method (so called p-square method) using free field, hemi-free field and diffuse field has been established, and they have been standardized in the international standards (ISO 3740 series) and in the national standards (JIS Z 8732-1986, JIS Z 8733-1987 and the draft of JIS Z 8734). Further, the method of sound power measurement using the sound intensity technique is now under preparation for an ISO standard (by ISO/TC 43/SC 1/WG 25).

On the other hand, concerning transient sound sources such as impulsive and intermittent sound sources, the way of describing and measuring their acoustic outputs has not been established.

In this paper, "sound energy level" which represents the total sound energy radiated by a single event of a transient sound source is first defined as contrasted with the sound power level. Subsequently, its measuring methods by the sound pressure methods and the sound intensity method are investigated theoretically and experimentally on referring to the methods of measuring sound power level.

2. DEFINITION OF SOUND ENERGY LEVEL

For a stationary sound source, the sound power level L_w is defined as follows (see Fig. 1 (a)).

$$L_w = 10\log_{10}\left(\frac{P}{P_0}\right) \tag{1}$$

where, P is the sound power radiated by a station-

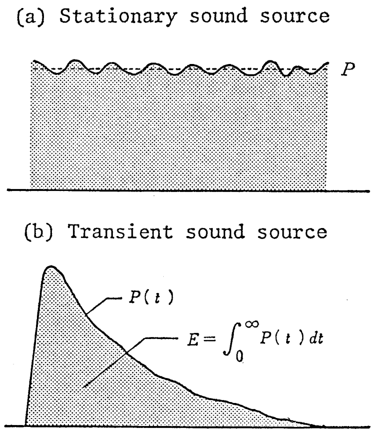

Fig. 1 Sound power of a stationary sound source and sound energy of a transient sound source.

ary sound source in W (=J/s), and P_0 is the reference sound power of 10^{-12} W.

In order to definitely represent the acoustic output of a transient sound source on referring to the definition of sound power level, we propose the following "sound energy level L_E" (see Fig. 1 (b)).[1-3]

$$L_E=10\log_{10}\left(\frac{E}{E_0}\right) \tag{2}$$

where E is the sound energy of a single event of a transient sound source in J, and E_0 is the reference sound energy of 10^{-12} J.

(Note) In the American National Standard ANSI S12.7-1986 (ASA 62-1986), L_E is used as the sign of "sound exposure level" which describes the time-integrated value of squared sound pressure of a single event. In this case, the subscript E might mean "exposure." In this paper, however, L_E is assigned to "sound energy level" to represent "energy" by the subscript E, and "sound (pressure) exposure level" is represented by L_{pE} as mentioned after.

3. METHODS OF MEASURING SOUND ENERGY LEVEL

The measuring methods of sound power level can be basically divided into following three ways.

1) The sound pressure method in free or hemi-free field

In this method, the sound intensity on a measurement surface enveloping a sound source located in a free or hemi-free field is approximated from the sound pressure on the surface, and then, the sound power of the source is obtained by integrating the sound intensity over the measurement surface.

2) The sound pressure method in diffuse field

The sound energy density in a diffuse field where a sound source under test is located is approximated from the sound pressure in the field, and then, the sound power of the source is obtained from the sound energy density and the equivalent sound absorption area (sound absorption power) of the measurement field (reverberation room).

3) The sound intensity method

The sound intensity on a measurement surface enveloping the sound source is directly measured by the technique of sound intensity measurement, and the sound power of the source is obtained by integrating it over the surface.

Concerning transient sound sources, there can exist similar three ways for the measurement of sound energy level as follows.

(A) The sound pressure method in free or hemi-free-field[1,3]

The instantaneous sound intensity component $\vec{I}(t)$ on a hypothetical sphere with radius r enveloping a transient sound source is expressed as:

$$\vec{I}(t)=p(t)\cdot\vec{u}(t) \tag{3}$$

where, $p(t)$ is the sound pressure and $\vec{u}(t)$ is the associated particle velocity.

In the far field of the source, Eq. (4) holds true between the sound pressure and the absolute value of the particle velocity, and therefore the absolute value of the sound intensity is expressed by Eq. (5).

$$u(t)=p(t)/\rho c \tag{4}$$

$$I(t)=p^2(t)/\rho c \tag{5}$$

where, ρc is the characteristic impedance of the air.

Here, let us consider the time-integrated value of the sound intensity (J/m^2) expressed as follows, and call it "sound intensity exposure."

$$e=\int_0^\infty I(t)\,dt=\frac{1}{\rho c}\int_0^\infty p^2(t)\,dt \tag{6}$$

Further, by expressing this quantity in decibel, let us call it "sound intensity exposure level."

$$L_e=10\log_{10}\left(\frac{e}{e_0}\right) \tag{7}$$

In this case, by adopting the following value as the reference sound intensity exposure e_0:

$$e_0=\frac{E_0}{S_0}=I_0\cdot T_0=\frac{p_0^2}{\rho c}T_0=10^{-12}\ \text{(J/m}^2\text{)}$$

where,

$$I_0=10^{-12}\ \text{W},\ T_0=1\ \text{s},\ S_0=1\ \text{m}^2$$

the following expression is derived from Eqs. (6) and (7).

$$L_e=10\log_{10}\left[\frac{1}{T_0}\int_0^\infty \frac{p^2(t)}{p_0^2}dt\right]=L_{pE} \qquad (8)$$

where, L_{pE} is "sound exposure level" specified in ANSI S12.7-1986 and it corresponds to "sound exposure level L_{AE}" specified in ISO 1996/1 and JIS Z 8731 when A-weighted sound pressure is evaluated. In this paper, let us call L_{pE} "sound pressure exposure level" to clearly discriminate it from "sound intensity exposure level L_e," because they have different physical meanings. However, Eq. (8) means that they are equivalent in the far field and therefore L_e can be obtained by measuring L_{pE}.

The total sound energy of a single event of a transient source is:

$$E=\int_S e\,ds \qquad (9)$$

where, S denotes the total area of the measurement surface. When a spherical measurement surface of radius r is adopted, the total energy is:

$$E=\bar{e}\cdot 4\pi r^2 \qquad (9')$$

where, $\bar{e}$ is the mean value of e on the measurement surface.

Accordingly, L_E of the transient sound source is expressed as follows.

$$\begin{aligned}L_E&=10\log_{10}\left(\frac{\bar{e}\cdot 4\pi r^2}{e_0 S_0}\right)\\&=\overline{L_e}+10\log_{10}\left(\frac{r^2}{r_0^2}\right)+11\\&=\overline{L_{pE}}+10\log_{10}\left(\frac{r^2}{r_0^2}\right)+11 \qquad (10)\end{aligned}$$

where, $\overline{L_{pE}}$ is the energy-mean value of L_{pE} over the spherical measurement surface, and r_0 is the reference length of 1 m.

As is mentioned above, the sound energy level of a transient source can be obtained by measuring the sound pressure exposure levels on the measurement surface. (In the case where measurements are made on a reflective plane in hemi-free field, 11 in Eq. (10) should be substituted by 8.)

Here, the measurement of sound power levels of stationary sound sources by the sound pressure method in free field is based on the following equation.

$$L_w=\overline{L_p}+10\log_{10}\left(\frac{r^2}{r_0^2}\right)+11 \qquad (11)$$

where, $\overline{L_p}$ is the energy-mean value of the sound pressure level on the measurement surface.

Between Eq. (10) and Eq. (11), the only difference is the first terms in the right sides. That is, L_p in Eq. (11) is the mean square value of sound pressure, whereas L_{pE} in Eq. (10) is the time-integrated value of squared sound pressure.

(B) The sound pressure method in diffuse field[1,3]

In the case that a transient sound source is located in diffuse field, the following energy-based equation can be considered approximately valid.

$$P(t)=V\frac{dE_d(t)}{dt}+\frac{cE_d(t)}{4}A \qquad (12)$$

or

$$\int_0^t P(\tau)d\tau=V\cdot E_d(t)+\frac{cA}{4}\int_0^t E_d(\tau)\,d\tau \qquad (12')$$

where, $P(t)$ is the instantaneous sound power (J/s) emitted by the source, $E_d(t)$ is the sound energy density (J/m^3) in the diffuse field, V is the air volume (m^3) of the diffuse field (reverberation room) and A is the equivalent sound absorption area (m^2) of the field.

In Eq. (12′), $E_d(t)$ becomes zero by making $t\rightarrow\infty$. Consequently, the total sound energy of a single event of the transient source is expressed as follows.

$$E=\int_0^\infty P(t)\,dt=\frac{cA}{4}\int_0^\infty E_d(t)\,dt \qquad (13)$$

Here, the following equation is valid in diffuse field.

$$E_d(t)=p^2(t)/\rho c^2 \qquad (14)$$

Consequently, Eq. (13) can be expressed as:

$$E=\frac{A}{4\rho c}\int_0^\infty p^2(t)\,dt \qquad (15)$$

Therefore, L_E can be expressed by:

$$L_E=L_{pE}+10\log_{10}\left(\frac{A}{S_0}\right)-6 \qquad (16)$$

As a result, the sound energy level L_E of a transient sound source can be obtained by measuring the sound pressure exposure level L_{pE} and the equivalent sound absorption area A which is derived from the reverberation time.

Here, the measurement of sound power levels of stationary sound sources by the sound pressure method in diffuse field is based on the following equation.

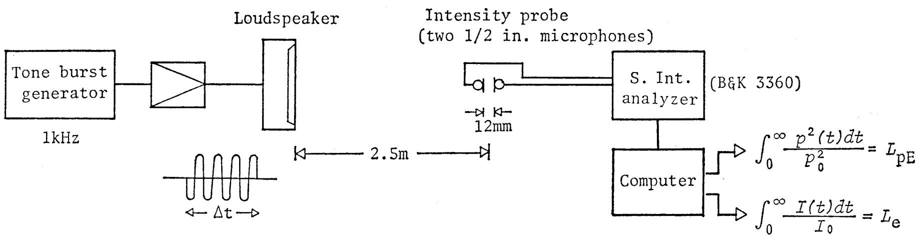

Fig. 2 Measurements of L_e and L_{pE} of tone bursts.

$$L_w = L_p + 10\log_{10}\left(\frac{A}{S_0}\right) - 6 \quad (17)$$

The difference between Eq. (16) and Eq. (17) is just the same as the difference between Eq. (10) and Eq. (11). That is, the sound power level of a stationary sound source is obtained by measuring the time-averaged value of squared sound pressure, whereas the sound energy level of a transient sound source is obtained by measuring the time-integrated value of the squared sound pressure. (In the actual measurements, L_{pE} in Eq. (16) and L_p in Eq. (17) should be obtained as the spatial mean values by measuring the sound pressure at many points in the diffuse field.)

(C) The sound intensity method[2,4,5]

The third way to obtain the sound energy level is the application of the sound intensity technique. In this method, the total sound energy can be obtained by measuring the instantaneous sound intensity on the measurement surface enveloping the sound source and by obtaining the sound intensity exposure e as the time-integrated value of the sound intensity (see Eq. (6)), and further by integrating the value of e over the whole measurement surface (see Eq. (9)).

This method using the sound intensity technique has an advantage that the measurement can be made even in the near field of a source where Eq. (4) is no longer valid. The measuring errors due to finite difference approximation inherent to the two microphone technique are determined by the relation between the highest frequency component in the transient sound and the distance between the two microphones.[4] This condition is just the same in the case where the sound intensity of a stationary sound is measured.

4. EXPERIMENTAL INVESTIGATIONS

4.1 Preliminary Study

As a preliminary study, the measurements of sound intensity exposure level and sound pressure exposure level were made. As shown in Fig. 2, a flat type loudspeaker (Technics SB-R100) was located in an anechoic room, and 1 kHz tone bursts of a constant amplitude and various duration times were radiated from it. At a point of 2.5 m from the loudspeaker, L_e and L_{pE} were measured according to (A) and (C) methods mentioned above, respectively. In this measurement, B&K 3360 sound intensity measuring system and two 1/2 inch condenser microphones (B&K 4165) which were separated by 12 mm were used.

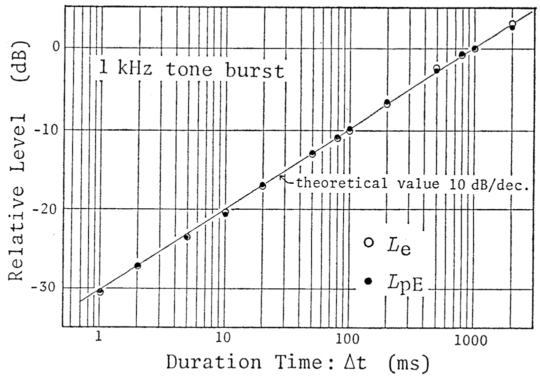

Fig. 3 Measured results of L_e and L_{pE} of tone bursts.

Figure 3 shows the measured results. In this figure, 0 dB is the sound pressure level or sound intensity level when the source signal was set stationary. In this result, it can be seen that the values of L_e and L_{pE} are markedly in good agreement as is expressed by Eq. (7), and they lie almost in the theoretical line of 10 dB/decade.

4.2 Measurements of Sound Energy Level and Sound Power Level

In order to examine the validities of the three kinds of measuring method mentioned above, the sound energy level of an artificial impulsive sound source was measured by these methods.

For the sound source, the loudspeaker mentioned above was used again, and two kinds of impulsive signal with duration times of 100 ms and 10 ms generated by a M-sequence signal generator were fed into it. Each of these signals was one sequence of M-sequence signal, and had sufficient repeatability.

At first, the measurement was performed in an anechoic room by locating the sound source on a reflective plane made up of concrete panels as shown in Fig. 4. Ten measuring points were chosen on a hemispherical surface of 1 m radius covering the source according to the prescription in ISO 3745 and JIS Z 8732, and L_{pE} in each 1/3 octave band was measured over the frequency range from 100 Hz to 10 kHz by (A) method (the hemi-free field method) and L_e in each 1/3 octave band was measured over the frequency range from 100 Hz to 5 kHz by (C) method (the sound intensity method). From these results, the sound energy level L_E was computed. In these measurements, the sound intensity system and the two microphones mentioned above were used again for the measurements of both of sound pressure and sound intensity.

Next, the sound source was located in a reverberation room of 200 m^3 air volume and the sound pressure exposure level L_{pE} in each 1/3 octave band from 100 Hz to 10 kHz was measured at five points in the room by (B) method (the diffuse field method). From the energy-mean value of L_{pE} and the equivalent sound absorption area obtained from the reverberation time measurement, L_E values were calculated according to Eq. (16). In this measurement, a free-field type 1/2 in. condenser microphone (B & K 4133) and a measuring amplifier (B & K 2134) were used, and the diffuse field corrections were made.

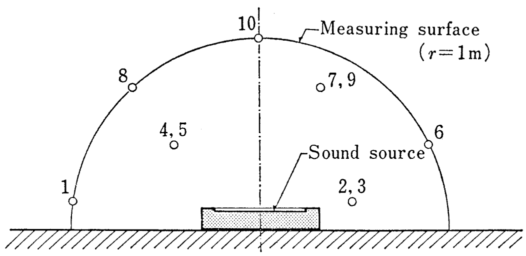

Fig. 4 Array of measuring points for the measurements in hemi-free field.

At the same time of the measurement of the sound energy level of the impulsive sound source mentioned above, the sound power level was measured by radiating a stationary random noise (M-sequence signal) from the same loudspeaker according to the

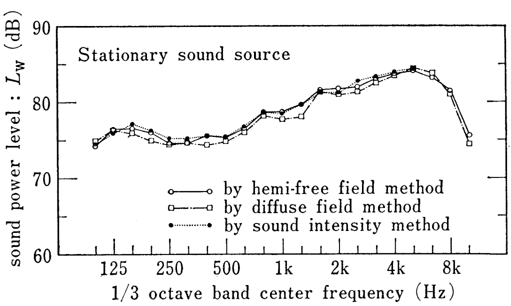

Fig. 5 Measured results of sound power level of the stationary sound source.

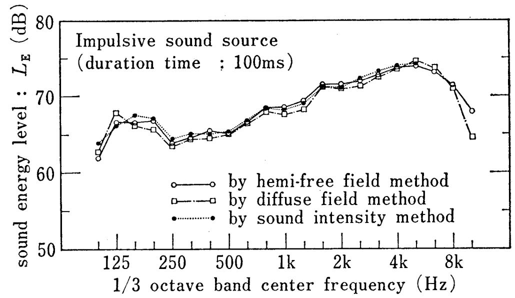

Fig. 6 Measured results of sound energy level of the impulsive sound source with 100 ms duration time.

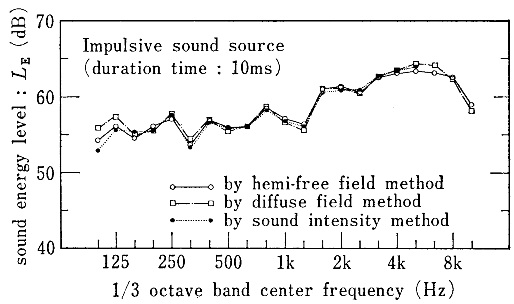

Fig. 7 Measured results of sound energy level of the impulsive sound source with 10 ms duration time.

three kinds of measuring method (the hemi-free field method, diffuse field method and the sound intensity method).

The measured results are shown in Figs. 5, 6, and 7. In the case where the sound source was stationary, the sound power levels measured by the diffuse field method are a bit lower than the other two kinds of results as shown in Fig. 5. However, the difference is 1.5 dB (at 1.25 kHz) at most and it can be considered within the acceptable error due to the difference of the measuring method of sound power level.

Next, in the case of impulsive sound source with 100 ms duration time, some differences of about 1.5 dB are seen in low frequency bands as shown in Fig. 6, but this can be also considered negligibly small. (A relatively big difference is seen in 10 kHz band between the result measured by (A) method and that by (B) method. It might be caused by the difficulties of measurement in high frequencies.)

In the case of impulsive sound source with 10 ms duration time, 3 dB differences is seen in the lowest frequency band of 100 Hz, nevertheless fairly good agreements can be seen in almost all frequency bands as shown in Fig. 7.

Although slight errors due to the differences of measuring principle and sound field are observed, fairly good agreements have been obtained among the results measured by the three kinds of measuring method in each measurement. From these results, it can be concluded that sound energy levels of transient sound sources can be obtained by the three kinds of measuring method investigated in this paper with almost the same accuracy as in the sound power level measurements of stationary sound sources.

5. CONCLUSIONS

As a physical property of a transient sound source such as an impulsive source, the total sound energy is essential besides the temporal characteristics. Therefore, in this paper, the way of defining the total acoustic energy radiated by a transient sound source has been proposed on referring to the sound power level of a stationary sound source, and its measuring method based on three kinds of principles have been investigated. As a result of the experimental studies, it has been found that these measuring methods have almost the same accuracies as in the sound power level measurements.

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