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A temporal integration model for loudness perception of repeated impulsive sounds

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A loudness perception model for repeated impulsive sounds that have exponentially rising and decaying envelopes was studied. The loudness of repeated impulsive sound is the same as that of a single burst of impulsive sound up to a certain repetition rate. A critical repetition rate R_0 beyond which the loudness increases with increase in repetition rate was found to lie between 0.2 and 0.7 Hz. In other words, the critical time period, $1/R_0$, was 2~5 s. If it is assumed, therefore, that our auditory system has a capacity to hold loudness sensation for 2~5 s, the result of our experiment can be explained. An integrator of loudness which has a rise time constant of 100 ms and a decay time constant of 5 s yields a good descriptor of the experimental results.

Keywords: Loudness, Temporal integration, Two time constants, Impulsive noise, Impulsive sound

PACS number: 43. 50. Pn, 43. 66. Ba, Cb, Mk

1. INTRODUCTION

We are exposed to various kinds of noises in our daily life, including impact and impulsive noises. Such impulsive noise is characterized by a very high peak level and an extremely short duration. Therefore, it has little effect on the value of the A-weighted equivalent continuous sound pressure level and the fifty percentile exceeded sound level, even though it is more annoying than coincident steady or slowly varying noise such as road-traffic noise. Although some objective corrections for impulsive noise have been proposed, the quantitative basis for such corrections has not yet been established. It is desirable, however, that we have a method applicable to various kinds of noises without any corrections. This paper describes the results of our continuing study on the loudness of impulsive noise. PSE's (Points of Subjective Equality) for loudness were obtained here for repeated bursts of impulsive noise.

The previous data shows that the loudness of impulsive sound depends not only its energy but also on the peak sound pressure level.[1,2] According to later results of a round robin test on the loudness of single bursts of impulsive sound, however, the effect of temporal features of single bursts of impulsive sound on its loudness is described by the sound exposure level (the square-integrated value of sound pressure) or the maximum output of an r.m.s. circuit with a time constant longer than 100 ms.[3,4] This difference seems to be attributable to the difference in the experimental methods.[5] The later results means that a simple model for temporal integration of acoustic energy can explain the loudness perception of a single burst of impulsive sound.[3,4] Loudness of repeated impulsive sounds, on the other hand, is not fully explained by this model.[6,7] Pollack obtained the equal-loudness contour for repeated bursts of noise, and found that the energy of interrupted noise was less than that of continuous noise for the same loudness.[8] Sone *et al.* investigated the relationship between the loudness and sound energy of repeated impulsive sounds that had exponentially rising and decaying envelopes.[7] As a result of experiments, Sone *et al.* showed that the increase in loudness with increase in repetition rate was less than that in sound energy. Thus, a new idea is required for the model to be applicable to the evaluation of repeated impulsive sound.

Although the relationship between the loudness and repetition rate does not follow the energy principle, repeated impulsive sound with relatively high repetition rate is felt louder than a single burst of impulsive sound with the same intensity, and the loudness of repeated impulsive sound comes down to that of a single burst as the repetition rate decreases. Thus, if the interval between two successive impulsive sounds is long enough, each burst of a series of repeated impulsive sound is perceived independent of each other. In other words, the loudness of repeated impulsive sound begins to increase above that of a single burst when its repetition rate exceeds a certain critical value. We call this critical value "the critical repetition rate for loudness perception of repeated impulsive sounds."

In this paper, the critical repetition rate is obtained from the results of two psychoacoustical experiments, and based on the results, a loudness perception model for repeated impulsive sound is proposed.

2. LOUDNESS OF REPEATED IMPULSIVE SOUNDS LASTING 50 SECONDS OR LESS

2.1 Experimental Procedure

The psychoacoustical experiment was carried out in order to obtain the relation between the loudness and the repetition rate of impulsive sounds. The constant method was used here. The subjects were asked to judge which burst was louder. The pair of sounds consisted of a test sound (impulsive sound) and a comparison one (a sound of two seconds duration) with a temporal pattern as shown in Fig. 1.

Table 1 shows the parameters of the stimuli. The impulsive sound used had an exponentially rising and an exponentially decaying part. The rise and decay time of a single burst of impulsive sound were 1 ms and 100 ms, respectively for a 20 dB change in level. The repetition rates were 0.2∼5 Hz. The total duration of a repeated impulsive sound was 1∼50 s. The number of repetitions was set to $\mathrm{INT}(D\cdot R)+1$, where D is the duration, and R is the repetition rate of the stimulus. $\mathrm{INT}(x)$ yields the largest integer less than or equal to x. The stimuli were digitally synthesized on a 32-bit minicomputer (TOSBAC DS-600) where a single burst of impulsive sound was generated and superimposed on the original sound with a certain time delay to create a repetitive impulsive sound. The synthesized stimuli were reproduced through a 16-bit D/A converter and recorded on video tape in EIAJ format for PCM code.

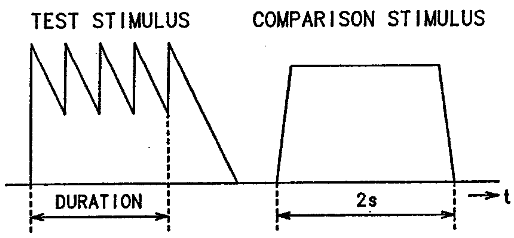

Fig. 1 The temporal pattern of a pair of stimuli used in the experiment.

Table 1 Experimental condition.

Peak level (phon)	85
Rise time* (ms)	1
Decay time* (ms)	100
Repetition rate (Hz)	single burst, 1/5, 1/2, 1, 2, 5
Duration(s)	1, 2, 5, 10, 20, 50

* The time for a 20 dB change in level.

Stimulus sounds were presented to the subjects via headphones, YAMAHA YHD-3, with a peak level of 82 dB SPL. This level corresponds to 85 phon in loudness level.[7] The comparison stimulus had the same carrier signal as the test stimulus, and its level was one of nine levels in a 20 dB range with 2.5 dB steps. The frequency response of the system was previously flattened by a graphic-equalizer, Technics SH-8065.

The carrier signal for both test and comparison sounds was an asymmetric rectangular wave similar to that used in the round robin test in Japan,[3,4,7] i.e., a mixture of two asymmetric rectangular waves with fundamental frequencies of 440 Hz and 1,175 Hz. The ratio of the amplitude of the 440 Hz component to that of the 1,175 Hz component was three to two. The duty cycle of the rectangular wave was set at 15% in order to get a wide frequency spectrum.

In stimulus presentation a comparison stimulus always followed a test stimulus. The reverse order was not used because of the difficulty in judgment. Stimuli were divided into four groups. One group had 1 s, 2 s and 5 s durations while the other had 10 s, 20 s and 50 s. This was done to avoid the difference in duration influencing the loudness judgment, and to overcome the difficulty in judgment when the stimulus of 1 s duration is presented just after that of 50 s duration.

The subjects were seven young adults with normal hearing. The number of repetitions for a level was 14. The ambient noise level in the listening room was less than 30 dB in A-weighted SPL. PSE's were estimated from the results of the experiment by using the method of maximum likelihood.[9]

2.2 Results

Table 2 shows the result of the analysis of variance applied to PSE's for loudness. The main sources in this analysis were subjects (7), durations (6) and repetition rates (5) of test stimuli. The SPSS[x] statistical package was used for the analysis with the ACOS-2000 computer of the Computer Center, Tohoku University. As shown in Table 2, all the main sources were significant beyond 0.01 points. The contribution (the square of partial correlation coefficient) of repetition rates (0.533) was far higher than those of subjects (0.032) and durations (0.063).

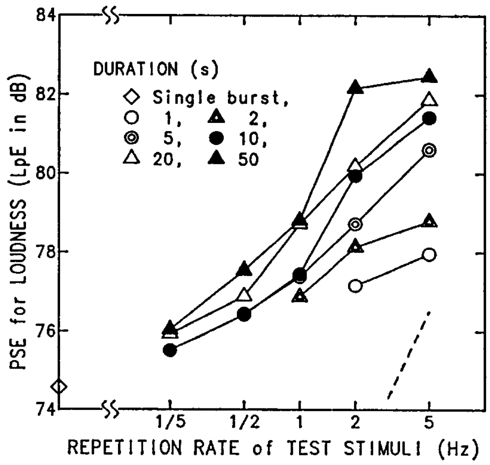

Fig. 2 Relation between PSE's for loudness and repetition rates of impulsive sounds.

Figure 2 shows the relation between repetition rates and PSE's for loudness. It is seen that the PSE for loudness of repeated impulsive sound is nearly proportional to the logarithm of the repetition rates ranging from 0.2 Hz to 5 Hz. This relation, however, does not follow the energy principle. PSE increases approximately 1.5 dB with doubling of the repetition rate.

2.3 Discussion

Results of the experiments show that the PSE for repeated impulsive sound is nearly proportional to the logarithm of the repetition rate, at least for the rates in the range of 0.2~5 Hz. Thus, we assume that the following equation represents the relation between the repetition rate and the PSE for loudness of repeated impulsive sound:

$$L_{PSE} = C \log(1 + R/R_0) + L_{PSE0}\,, \qquad (1)$$

where C is a constant, R is the repetition rate, R_0 is the rate corresponding to the point of intersection of two asymptotes, the one for R being 0 (single burst) and the other for R being ∞ (steady sound), and L_{PSE0} is the PSE for loudness of a single burst of impulsive sound.

Figure 3 gives the intersection of asymptotes. Table 3 shows the estimated R_0's for the results of our experiment. From this table, we find that the critical repetition rate R_0 is in the 0.2~0.5 Hz range, with an average of 0.3 Hz and the critical interval

Table 2 Result of analysis of variance.

Source of variation	Sum of squares	DF	Mean square	F	Contribution ratio
Main effects	700.897	15	46.726	47.882	
Subject	27.252	6	4.542	4.654**	0.032
Duration	223.432	5	44.686	45.792**	0.063
RR	620.000	4	155.000	158.835**	0.533
Explained	700.897	15	46.726	47.882	
Residual	148.330	152	0.976		
Total	849.227	167	5.085		

* Significant beyond 0.05 point.
** Significant beyond 0.01 point.

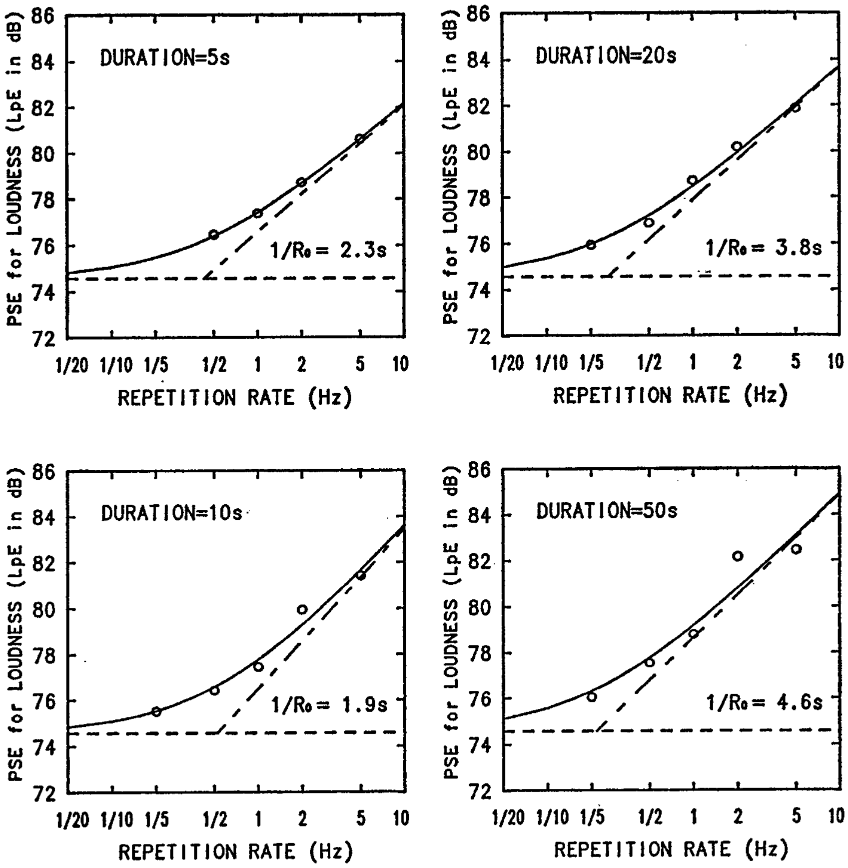

Fig. 3 PSE for loudness of repeated impulsive sounds as a function of the repetition rates. The same data as shown in Fig. 2 were used. Two asymptotes were drawn on the basis of Eq. (2). The broken line (horizontal) shows the PSE for loudness of single burst of impulsive sound. R_0 is defined as the value of repetition rate at which the two asymptotes intersect.

Table 3 The critical repetition rate R_0 and the corresponding time $1/R_0$—estimated results.

Duration (s)	R_0 (Hz)	$1/R_0$ (s)
5	0.428	2.3
10	0.527	1.9
20	0.263	3.8
50	0.217	4.6

$1/R_0$ is in the range $1.9\sim4.6$ s, with an average of 3.2 s. This interval is thought to relate to the *psychological present*, which is considered to coincide with the duration during which the sensation of sound lasts.[10,11]

The *psychological present* is defined as the time limit of perception, i.e., the duration of perception corresponds to the transition from a *judgment by perception* to a *judgment by memorization.* The *psychological present* is not an unique technical term, and has also been called "the present-time" of "the perceptual present." Teranishi[12] points out that the *psychological present* is a time window in perception, and that the width of the window is uncertain because of its gradual shape. The fact that $1/R_0$ varied from 1.9 s to 4.6 s may be explained as caused by the uncertainty of the width of the time window.

As a result it can be assumed that the auditory system keeps the sensation of loudness up to the time $1/R_0$ (about 3 s).

2.4 Analysis of the Results from the Round Robin Test

The research group including the authors carried out two stages of the round robin test from 1981 to 1987 in order to establish a method for evaluating impulsive sound. Experiments on loudness of a single burst of impulsive sound were executed in the first stage of the round robin test.[3,4] Loudness and

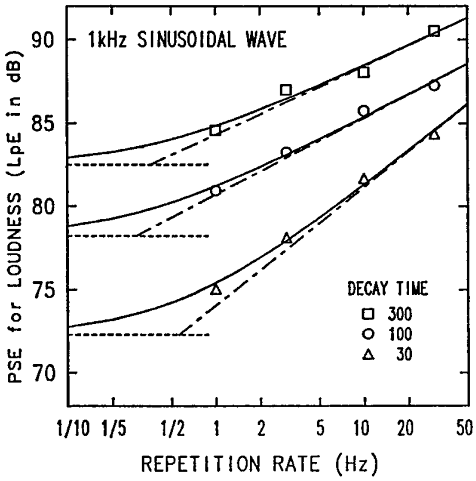

Fig. 4 Relation between PSE's for loudness and repetition rates of impulsive sounds. The data obtained in the round robin test[7] were plotted here. The carrier signal was a 1 kHz sinusoidal wave.

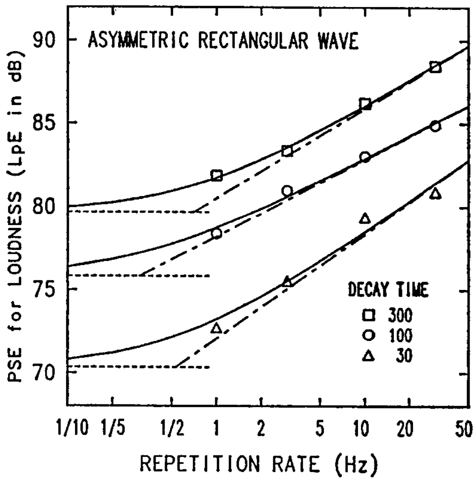

Fig. 5 The same relation as in Fig. 4 except that the carrier was an asymmetric rectangular wave.

noisiness of repeated impulsive sound were investigated in the second stage.[7] Results from the second test are analyzed here. The relation between PSE's for loudness and repetition rates is examined in the same manner as in the previous section.

In the experiments, the repetition rates of stimuli were from 1 Hz to 30 Hz, while the durations were from 2 s to 3 s. The experimental procedure was similar to that stated in section 2.1. The carrier signals for the stimuli were either a 1 kHz sinusoidal wave or asymmetric rectangular waves.

Figures 4 and 5 show the relation between PSE's

Table 4 R_0 and $1/R_0$ estimated from the results in the round robin test.

Carrier	Decay time (ms)	R_0 (Hz)	$1/R_0$ (s)
1 kHz sinusoidal wave	30	0.561	1.8
	100	0.288	3.5
	300	0.360	2.8
Asymmetric rectangular waves	30	0.532	1.9
	100	0.304	3.3
	300	0.705	1.4

for loudness and the repetition rates of impulsive sounds. Table 4 shows the values of R_0 and $1/R_0$ estimated from the experimental results. $1/R_0$ is about 2.4 s, on the average. This value is roughly the same as that obtained in the last section (3.2 s). From the results of the last section and the present section, $1/R_0$ is estimated to be approximately 3 s.

3. LOUDNESS PERCEPTION MODEL FOR REPEATED IMPULSIVE SOUND

3.1 Loudness Evaluation with the I, F and S Detector-Indicators

The effect of duration of tone burst on loudness has been investigated by many researchers.[13-16] Munson,[17] Zwislocki[18] and Robinson[19] put forth the *running-average hypothesis* and applied it to a model for the temporal integration of loudness. According to the researchers, time constants in the temporal integration model varied from 50 ms to 300 ms. As for impulsive sound, loudness of a single burst of impulsive sound is well explained by the sound exposure level or the output level of a temporal integration model with a single time constant.[3,4,20,21] Moreover, from the results of the previous section, it is assumed that our auditory system holds the integrated sound energy for about 3 s. Thus, a model for loudness perception includes at least two different time constants. Both of the models, with a single and two time constants, are examined in this section.

The output from the temporal integration model with a single time constant can be expressed by

$$y(t)=\int_0^t w(\lambda)x^2(t-\lambda)d\lambda\ , \qquad (2)$$

where $x(t)$ is the input signal and $w(t)$ is a time weigting function given by

$$w(t)=\exp(-\alpha t)\,, \qquad (3)$$

where $1/\alpha$ is a time constant.

The circuit represented by Eq. (2) has the same averaging mechanism as the F and S detector-indicator characteristics of a sound level meter, when the time constant is 125 ms and 1 s respectively. Figures 6 and 7 show the relation between PSE's for loudness and the peak levels through the F and S detector-indicators, where ⟨E⟩ is the r.m.s. value of the differences in dB between the experimental PSE and the estimated PSE. If the transverse axis is a good descriptor of loudness evaluation, ⟨E⟩ should have a small value. The broken line represents the state where the PSE's are equal to the values obtained with our model. When the F or S detector-indicator is used, ⟨E⟩ is very large, and in the most cases, the peak levels through the F and S detector-indicators are found to be less than the PSE's for loudness.

Now, it is assumed that a temporal integration model for loudness perception of repeated impulsive sound has two kinds of time constants and is achieved by means of an r.m.s. detector with short averaging time and an energy holder with a long fall time. The I detector-indicator characteristic consists of an r.m.s. detector and a peak holder, so that the I detector-indicator acts as a good loudness evaluator. Figure 8 shows the block diagram of the I detector-indicator. Figure 9 shows the result of

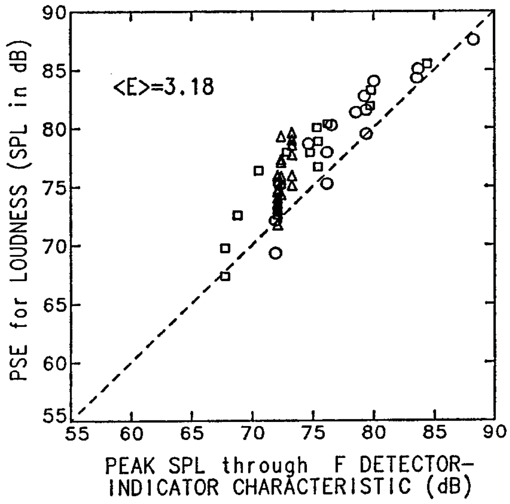

Fig. 6 Relation between PSE's for loudness and the peak levels of stimuli based on F detector-indicator characteristics. ⟨E⟩ is the root mean square of the difference between output level of the model and PSE for loudness.

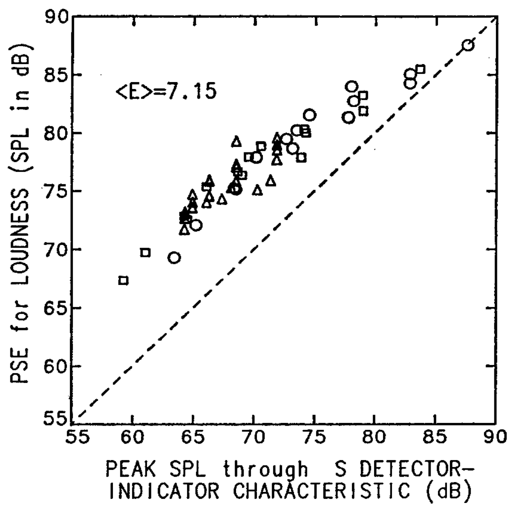

Fig. 7 Relation between PSE's for loudness and the peak levels of stimuli the based on S detector-indicator characteristics.

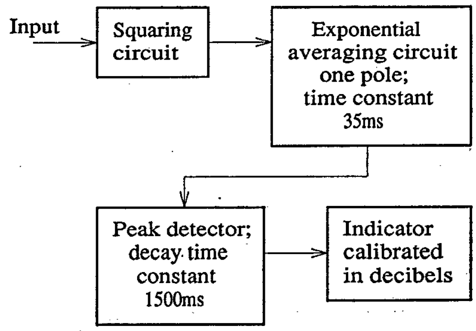

Fig. 8 The block diagram for obtaining I detector-indicator characteristics (IEC Pub. 651).

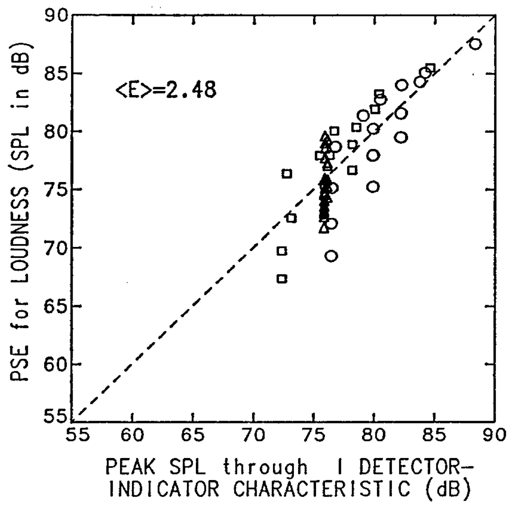

Fig. 9 Relation between PSE's for loudness and the peak levels based on I detector-indicator characteristics.

loudness evaluation with peak level through the I detector-indicator. The peak levels of outputs from the I detector-indicator does not explain the fact that the PSE's for loudness of repeated impulsive sound is proportional to the logarithm of the repetition rates.

3.2 Loudness Evaluation with the Two-Time-Constants Model

A low-pass filter circuit with a short time constant for charging and a long time constant for discharging behaves as if the circuit consists of an r.m.s. detector and an energy holder. It is called the *two-time-constants circuit* (or *model*) in this paper.

The behavior of the two-time-constants circuit is also expressed by Eqs. (2) and (3), except that the time constant $1/\alpha$ is defined by

$$1/\alpha=\begin{cases}\tau_r, & x^2(t)>y(t)\\ \tau_a, & x^2(t)\leq y(t),\end{cases} \tag{4}$$

where τ_r is the time constant in the temporal loudness integration and τ_a is the time constant of the holder of sound energy. Since the time constant in the temporal integration of loudness is said to be from 50 ms to 300 ms, τ_r is assumed to be 50～300 ms. However, τ_a has not been obtained clearly till now.

If τ_a is 3 s or a few seconds more than that, the model expressed by Eqs. (2) and (3) can hold the sound energy for about 3 s. We calculate the appropriate rise and decay time constants by the least mean square method, to explain the experimental results mentioned above. As the result, the optimum rise and decay time constants are found to be 100 ms and 5 s, respectively. The rise time constant of 100 ms and the decay time constant of 5 s yield the results which correspond well with the experimental results shown in section 2.2. Figure 10 represents the PSE's for loudness expressed by peak outputs through the model with $\tau_r=100$ ms and $\tau_a=5$ s. Since the ⟨E⟩ obtained in this model is small compared with those obtained in other models, the two-time-constants model with $\tau_r=100$ ms and $\tau_a=5$ s is found to be appropriate for loudness perception of repeated impulsive sound.

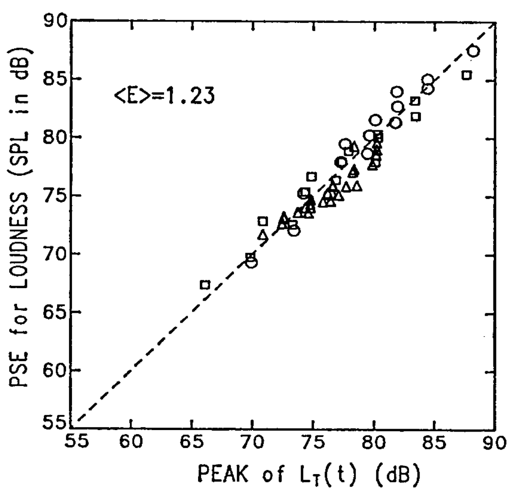

Fig. 10 Relation between PSE's for loudness and the peak levels of stimuli based on the model.

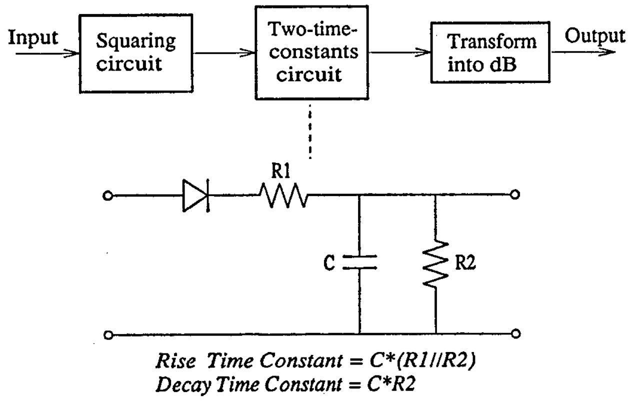

Fig. 11 The block diagram of the two-time-constants model and its equivalent circuit that have a short rise time constant and a long decay time constant.

The loudness integration model characterized by Eqs. (2) and (3) is realized by a simple electric circuit using a diode, two resistors and a capacitor as shown in Fig. 11. The instantaneous output level $L_T(t)$ in this circuit is expressed by

$$L_T(t)=10\log_{10}\{y(t)/y_0\}, \tag{5}$$

where y_0 is the output from the model corresponding to a 20 μPa input.

The equivalent continuous output level L_{Teq} averaged over the time interval from t_1 to t_2 is defined by the following equation:

$$L_{Teq}=10\log_{10}\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2}\{y(\lambda)/y_0\}d\lambda\right] \tag{6}$$

4. DISCUSSION

Integrators with two time constants are used in the current standards for description and measurement of environmental noise. One of them is described by the I detector-indicator characteristic of a sound level meter as prescribed in IEC Pub. 651.[22] The principle of the I detector-indicator is

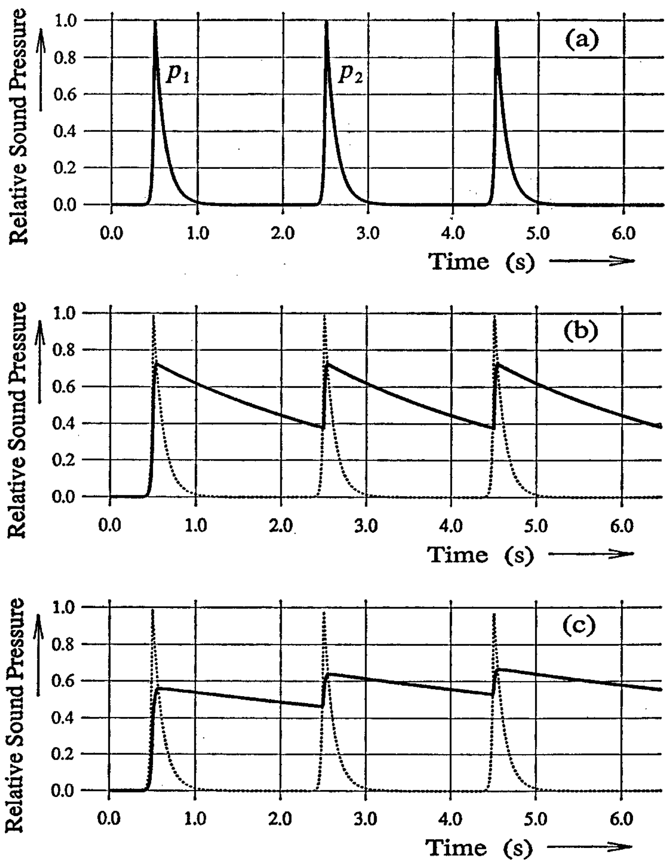

Fig. 12 The difference between the outputs based on the I detector-indicator and the two-time-constants model (a) input signal, (b) output based on the I detector-indicator characteristic, (c) output based on the two-time-constants model.

different from that of the two-time-constants model introduced in the last section. The I detector-indicator consists of an integrator (r.m.s. circuit) and a peak holder (Fig. 8), while our two-time-constants model is composed of an integrator which has a short rise time constant and a long decay time constant (Fig. 11). In order to check the difference between the two integrators, we assume that a repetitive input signal shown in Fig. 12(a) is applied to both the I detector-indicator and the two-time-constants model. Figure 12(b) is the output through the I detector-indicator. As shown in Fig. 12(b), the peak value of the output of the I detector-indicator caused by input p_1 is held with a time constant of 1.5 s. When p_2 is input, the I detector-indicator discards the held value and keeps the peak value caused by p_2. Thus, the peak of the output through the I detector-indicator is constant independent of the repetition rate. Figure 12(c) shows schematic output through the two-time-constants model. When the same signal is input, the peak of the output increases with the repetition rate because peak induced by p_1 has a pedestal effect on the output related to p_2. Therefore, the two-time-constants model can explain the increase in loudness for a repeated impulsive sound with repetition rate, while the I detector-indicator cannot.

The I detector-indicator has another defect—the time constant of 35 ms is too short. Several researcher showed that the 35 ms time constant is inappropriate for the prediction of the loudness of the impulsive sounds.[8,23] Sone *et al.*[8] showed that the F (125 ms) or S (1s) detector-indicators are applicable for evaluating loudness of a single burst of impulsive sound, while the I detector-indicator is inappropriate for evaluating loudness of sound because the time constant of the I detector-indicator is too short.

Advantages of the integrator with two-time-constants for explaining loudness integration are already discussed by some other researchers. Models presented by Port,[24] Kumagai *et al.*[25] and Kado[26] are similar to ours.

Port[24] used the model in order to evaluate the loudness of repeated burst of sound. Kumagai *et al.*[25] investigated how to measure the loudness of repeated impulsive sound using sound stimuli with relatively short duration ($\sim$1.4 s). He proposed a circuit that consists of two two-time-constants integrators connected in parallel. One of the two-time-constants integrators in the Kumagai's model seems to correspond to the one proposed here. However, the decay time constants of their models are far shorter than that proposed by the present study. Port estimated the decay time constant at 700 ms and Kumagai *et al.* estimated it at 250 ms. Port studied the effect on loudness of impulsive sound by varying the repetition rate from 2 to 500 times per second. This means that in his experiment pulses appeared at least once every 0.5 s. Kumagai *et al.* used stimuli with a maximum duration of 1.4 s. It is difficult, under such conditions, to assess an appropriate time constant for the evaluation of actual repeated impulsive sound because the repeated impulsive sound sometimes coexists with slowly-varying noise and sometimes has very low repetition rate ($<$1 Hz). The shorter decay-time-constants such as suggested by Port and Kumagai *et al.* are applicable only to evaluate the loudness of repeated impulsive sound with a high repetition rate and short duration. In the present study, the maximum duration of the stimuli was 50 s. Thus the minimum repetition rate could be reduced to 0.2 Hz. Therefore, the time constant estimated in this study is expected to be applicable to the evaluation of actual impulsive noises found in the environment.

Kado[26] studied the loudness of a fluctuating sound. He also introduced a loudness integrator with two time constants to explain the loudness of a fluctuating sound. He estimated the decay time constant to be 700~1,000 ms, considering *Short Term Storage* at the central nerve. However, he did not mention in his paper how he determined the decay time constant. Moreover, he said that he was not confident of the value of the constant. We suppose that the decay time constant corresponds to the transition from a *judgment by perception* (*the psychological present*) to a *judgment by memorization* (*the short term storage*). From this point of view, the *psychological present* for the loudness of sound could be estimated at 3 s and the corresponding time constant at 5 s. Experimental results by Nakamura seem to support this.[11] Nakamura studied the relation between loudness and the equivalent continuous sound level of repeated impulsive sounds. She found that the equivalent continuous sound level in about 3 s corresponds to the loudness of stimuli used in her experiment. She stated that three seconds is the duration which is most easily perceived in a group and that this duration is similar to the length of psychological present after Fraisse.[10]

As stated above, the present model is expected to yield a good descriptor to evaluate the loudness of an impulsive sound with various repetition rates including very low rates. Now, we examine if this model can evaluate the loudness of a repeated impulsive sound with very high repetition rates (>30 Hz). Carter investigated the relation between the peak levels and the repetition rates for the pulse with a rise time constant of 0.5 ms and a duration of 1 ms.[27] The highest repetition rate was 128 Hz in his experiment. His experiment is characterized by a short duration and high repetition rate of the stimuli. He found that the loudness level of the stimuli used in his experiment is proportional to the acoustic energy level, i.e., the energy principle is applicable to the results.

We reproduced Carter's stimuli and evaluated the loudness with our two-time-constants model. Figure 13 shows the equal-loudness curve obtained by the

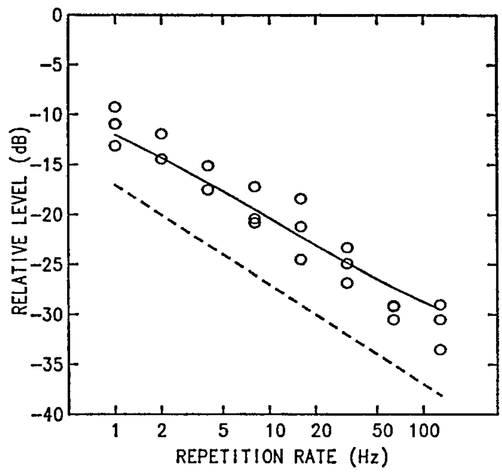

Fig. 13 An example of loudness evaluation by using the present method for triangular transients. Carter[27] investigated the relationship between the peak levels and the repetition rates of triangular transients under the condition of equal-loudness. In the figure, the solid line shows L_{Teq} obtained through our model and the broken line corresponds to the case where the loudness follows the energy principle.

proposed method and the data by Carter. The output through the two-time-constants model roughly corresponds to the data presented by Carter. Therefore, the two-time-constants model is also useful in evaluating the loudness of stimuli with a short duration and high repetition rate.

In this paper, we showed that the two-time-constants model could evaluate the loudness, not only for a single burst of impulsive sound, but also for a repeated impulsive sound with equal peaks and regular repetition rates lasting 50 s or less. However, real impulsive sounds sometimes have uneven peaks and irregular repetitions. Therefore, we cannot conclude from the results of this study that the two-time-constants model can correctly evaluate the loudness of irregular impulsive sound or the sound consisting of steady and impulsive components. We expect, however, that the two-time-constants model is useful for irregular and complex sounds.

As described in Eq. (5), the output of the two-time-constants model is the time-varying function of loudness weighted by the time window (few seconds). Thus, the instantaneous output of the model varies with the changing peak and repetition rates of the sound. Therefore, we believe that the two-time-constants model can correctly estimate the instantaneous loudness for the repeated impulsive sound with varying peaks and repetition rates. For estimating the overall loudness of repeated impulsive sound, the longterm L_{Teq} seems to be useful. In the future we plan to investigate the validity and range of applications for L_{Teq}.

The loudness evaluation method proposed in this paper is also useful for steady sounds. When a steady sound is supplied to the two-time-constants model, the influence of the decay time constant (5 s) on the model output is quite small. On the other hand, the influence of the rise time constant (100 ms) is prominent. Thus, the output from the model for a steady sound is almost the same as the output from a single time constant circuit with a time constant of 100 ms. According to many researchers,[13-19] when a tone burst is supplied the time constant of the human auditory system ranges from 50 ms to 300 ms. Therefore, the proposed model has time constants in conformity with those obtained in previous studies. Also, the model correctly evaluates the loudness of steady sounds.

5. CONCLUSION

The loudness of sound including single and repeated bursts of impulsive sound is examined with the intention of developing a new model for loudness evaluation applicable to repeated impulsive sounds. The loudness of impulsive sounds with exponentially rising and decaying envelopes was studied as a function of repetition rate. As a result, the critical repetition rate at which the loudness of a repeated impulsive noise began to increase beyond that of a single burst was found to be about 0.3 Hz and this value was assumed to show that the auditory system has the capacity to hold the sensation of loudness for about three seconds. A temporal summation model with two time constants was realized on the basis of this assumption. The rise and decay time constants were taken to be 100 ms and 5 s, respectively, based on the experimental results.

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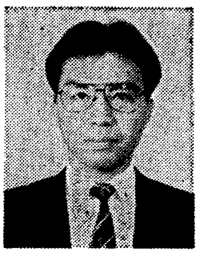

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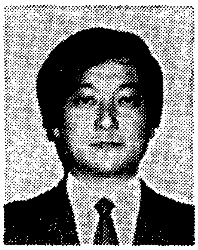

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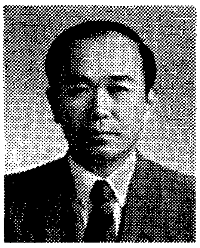

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