# Loudness of an impact sound

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The transient response of our hearing system was measured for the linear part with 0.05ms rectangular pulse. When a positive and a negative rectangular pulse with the same amplitude were given horizontally from the opposite directions, they were heard as loud as both were positive. It means that after the linear process a sound is absolutized. Thus the loudness of an impact sound is supposed to be determined with the integration over a time window for the absolute value of the convolution between a sound and the impulse response of our hearing system. Eight kinds of impact sounds were recorded and each was reproduced with three different levels. Twenty-four impact sounds were prepared for pair comparison and they got each figure on the Thurston's scale. Now the figure is the outsider for the Theory of Quantification I having a factor of time window. It was shown that the time window of 40ms has the largest multiple- correlation coefficient and is most proper for an impact sound to find its loudness.

**Keywords:** Loudness, impact sound, time window, absolutization

## Introduction

The linear part of our hearing system was found [1] to have a pair comparison of the loudness of two rectangular pulses with that of a single rectangular pulse, changing their time intervals (See Fig.1). The rectangular pulse had 0.05ms time duration, which covers our audio frequency range, and had the amplitude of 93dB or 87dB. Now it is called as the impulse response of our hearing system.

This linear response, shown in Fig.1 is supposed to include the head related transfer function (HRTF), the elastic response of the eardrum to the three little bones, the lymph liquid in the cochlea, and the elastic movement of the basilar membrane. It might include even a part of peripheral nerve system.

When a positive and a negative rectangular pulse of the same amplitude were given from opposite directions as in Fig.2, they were heard as the same loudness as if they were two positive rectangular pulses. It was shown that there is a process to make a sound absolutized [2] after the linear process. It is discussed in this paper how the loudness of an impact sound is decided at the higher level. It is tried to find how it weighs on frequency and forms a time window.

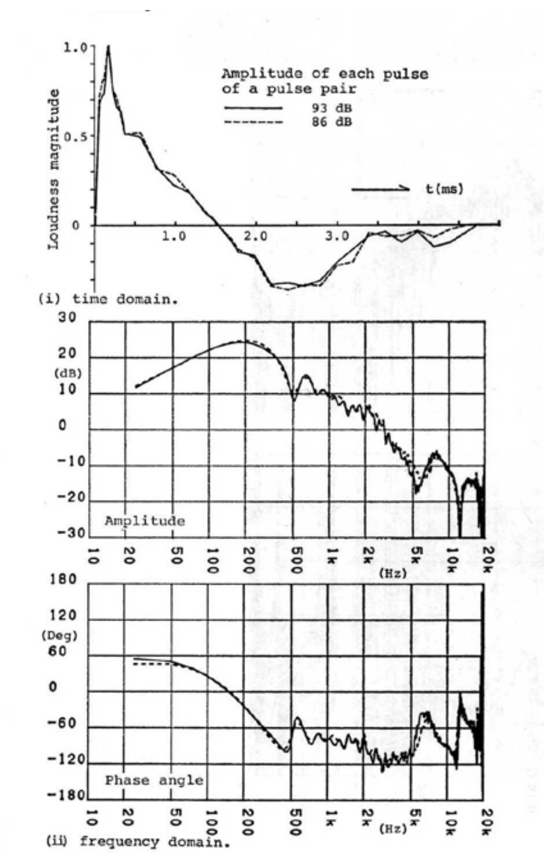



Fig.1. Impulse response of our hearing system and its frequency characteristics

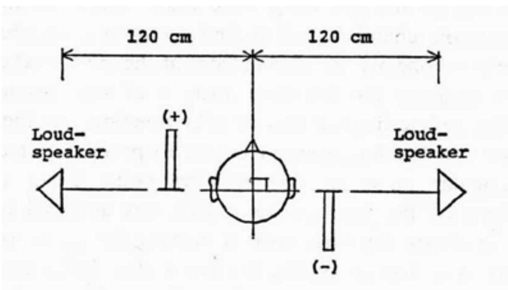



Fig.2. A positive and a negative rectangular pulse from opposite directions

**(1). Thurston scale by pair comparison for various impact noises**

First, eight kinds of impact sounds were ecorded with slight adjustment as shown in Fig.3. Each impact sound got three different levels with an 8dB step and 24 impact noises were prepared. Three peak levels for each impact sound are given in Fig.3.

Pair comparison was done in the anechoic chamber at Kansai Univ. by 18 test persons. At the pair comparison, another pair sound was given at 3.5 seconds [1] after the first impact sound was ceased. The combination for a pair was not reversely done and it was the pairs of 24 x 23 / 2.

After 24 impact sounds got the pair comparisons, they got the Thurston's scale in the case V and were arranged on one axis as in Fig.4.

The linear response of our hearing system and its absolutization process are shown previously. The next process is supposed to have the integration in a time window. It is expressed as in the equation(1)[3],

$$L = F\{\int_{t_1}^{t_2} | P(t) * R(t) | dt\} \tag{1}$$

where P (t) is a given sound pressure which is an impact sound in Fig.3. R (t) is the impulse response of hearing system in Fig.1 to be convolved. ＊ shows convolution product. From $t_1$ to $t_2$

is the interval of a time window for the

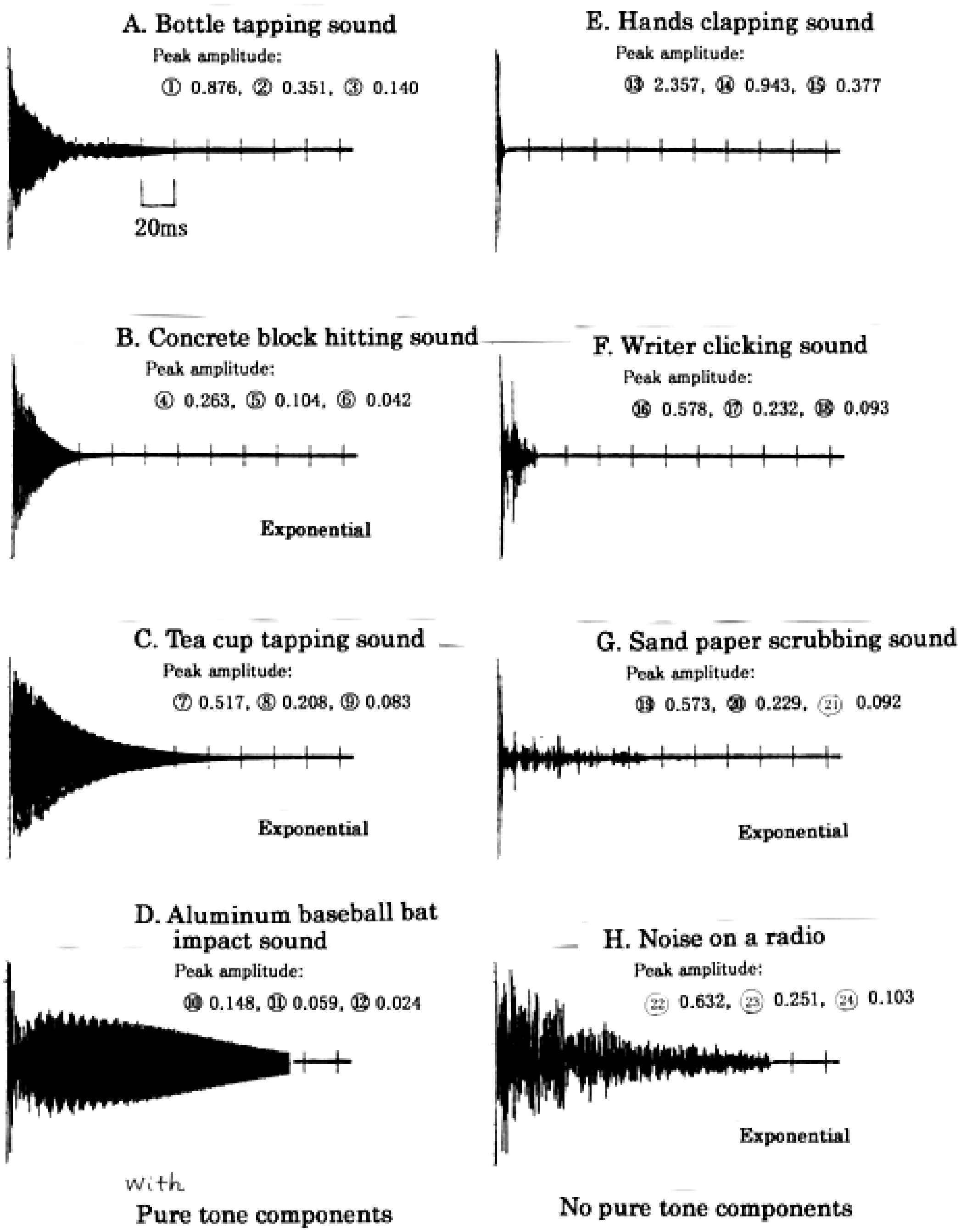



Fig.3. Eight kinds of impact sounds used for the pair comparison

Each impact sound gets three different levels whose peak amplitudes are shown.

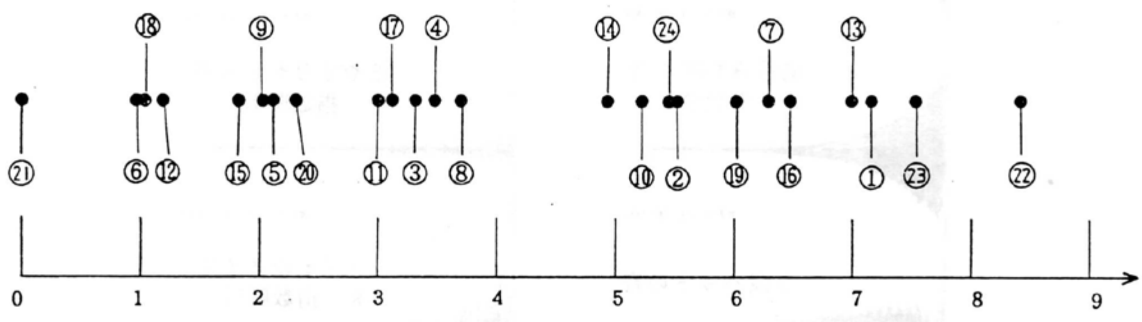



Fig.4. Loudness on the Thurston's scale for the 24 impact sounds in Fig.3

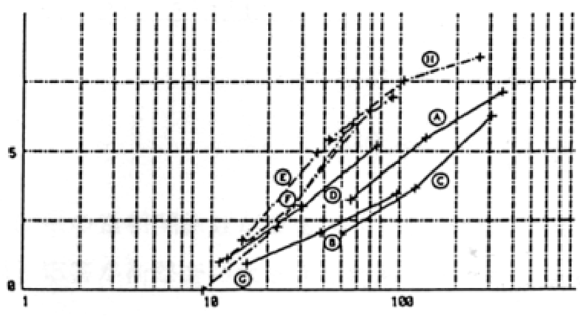
integrand. F { } is a function of power or logarithmic. Here the latter is used practically $20\log_{10}$ to get a decibel.

For the function R (t) in Eq. (1) to convolve to each impact sound, (a) unity to have the physical pressure itself, (b) "A" weight without any phase angle and (c) the impulse response of our hearing system were examined respectively. After then they were absolutized and integrated for 40ms as an example.

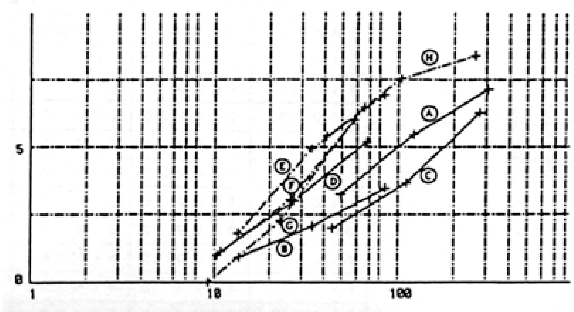
A decibel value is obtained for the integrated value in Eq. (1) and is given on the horizontal axis. The corresponding Thurston's scale is given on the vertical axis for each R (t) as shown in Fig.5. Each has three different levels and they are connected by a line.

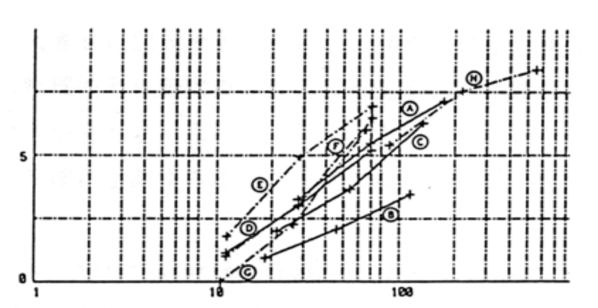
The decibel value of the integration of Eq. (1) correlates to the Thurston' scale at each R (t). It shows that the logarithmic scale has been well used for estimating the loudness level of a sound.

In each figure, each line is shifted almost in parallel. It suggests that there exist independent factors to explain the relation better. It seems that the distribution range of lines is smallest for the case of (c).



(a) An impact sound itself





(b)Convolution of "A" weight
(c) Convolution with the impulse response of our hearing system in Fig.1

Fig.5. Thurston's scale vs. integration of Eq. (1) after the convolution (a) of an impact sound only, (b) with "A" weight and (c) with the impulse response of our hearing system. The vertical axis shows the Thurston's scale. Ⓐ～Ⓗ shows an impact sound in Fig. 3.

**(2). Time window with the application of the Theory of Quantification I**

Having the Thurston's scale as an outsider and a variety of time window as a factor, Theory of Quantification I was applied to see how a multiple-correlation coefficient changes. It was searched which time window shows the largest multiple-correlation coefficient. It must be the most proper time window.

An impact sound is convolved as it was done in the previous section: (a) unity to have a physical impact sound, (b) "A" weight without any phase angle and (c) the impulse response of our hearing system. After each convolution, it is absolutized and integrated with a variety of time window.

The integration with a time window was converted to the decibel value with $20\log_{10}$. It was categorized with a 5dB step. Categories for the convolution of (a), (b) and (c) in the above are varied from 7 to 9. The result is shown in Table 1.

It shows that the largest multiple-correlation coefficient among three convolving functions for every time window was with the impulse response of hearing system. Namely, it says that it is most proper for weighing to our hearing attitude.

And at the time window of 40ms the multiple-correlation coefficient is the largest for the outsider of the Thurston's scale. It is the best time window for an impact sound.

Selected impact sounds in the left column of Fig.3 include pure tones. It was quantified with Theory of Quantification I as another factor for pure tones done with two factors. At the time windows other than 40ms, the internal correlation-coefficients were large and the results were not reliable. When the time window was 40ms it was accidentally small with 0.087. However, the multiple-correlation coefficient changed only from 0.9322 to 0.9357. It is not affected by the factor of pure tone. It might have been accepted as a part of the noise.

Possible additional factors should be

Table 1. Multiple-correlation coefficients by the Theory of Quantification I for three different convolution functions to R (t) in the integral Eq. (1)

(a) an impact sound itself, (b) “A” weight without any phase angle, and (c) the impulse response of our hearing system

| Time window | Multiple Correlation Coef | | | Time window | Multiple Correlation Coef | | |
|---|---|---|---|---|---|---|---|
| | (a) | (b) | (c) | | (a) | (b) | (c) |
| 10ms | 0.8474 | 0.8399 | 0.9165 | 90ms | 0.8286 | 0.8296 | 0.9181 |
| 20ms | 0.8560 | 0.8545 | 0.9127 | 100ms | 0.8211 | 0.8296 | 0.9003 |
| 30ms | 0.8490 | 0.8500 | 0.9129 | 110ms | 0.8211 | 0.8301 | 0.9003 |
| $\boxed{\text{40ms}}$ | 0.8644 | 0.8764 | $\boxed{0.9322}$ | 120ms | 0.8216 | 0.8214 | 0.9003 |
| 50ms | 0.8838 | 0.8855 | 0.9299 | 130ms | 0.8216 | 0.8214 | 0.8957 |
| 60ms | 0.8792 | 0.8940 | 0.9159 | 140ms | 0.8216 | 0.8214 | 0.8931 |
| 70ms | 0.8670 | 0.8291 | 0.9164 | 150ms | 0.8488 | 0.8352 | 0.8931 |
| 80ms | 0.8670 | 0.8222 | 0.9181 | 160ms | 0.8488 | 0.8352 | 0.8931 |

discussed considering the parallel shift in Fig.3 (c) and the multiple- correlation coefficient 0.9322 because it is less than unity.

**(3). Summary from the above results**

The loudness of an impact sound is estimated as follows:

O First the impulse response of our hearing system is convolved to a given impact sound. If it has an incident angle, its normalized directivity must be convolved.

O Before each signal comes to the binaural hearing process, it is absolutized.

O Meantime, a path way is chosen for the signal;

For instance, a pure tone from outside does not beat with the low pitch sound, the resonance frequencies at the external ear are smoothed at the transient response for the rectangular pulse of 0.05ms. Path ways for a rectangular pulse and a pure tone seems to be different.

O 40ms is the best time window for deciding the loudness of an impact sound.

O A loudness level is given by the

logarithmic expression.

## (4). Discussions

### (4-1). Absolutization in the hearing system and sound field estimation with intensity

The estimation of a sound is done with the loudness that is obtained from Eq. (1) with the time window, for instance, 40ms for an impact sound. This attitude of listening sound is done to every direction being convolved with the normalized directivity. After then it is absolutized.

A diffusive sound field does not have any particular direction to hear. The above attitude to listen sounds there shows that energetic treatment with the amplitude of a microphone in a sound field explains well a noise environment. But if a sound field is coherent or has a dominant direction of incidence, it must be careful that the output of a microphone does not always decide the loudness as pointed in the ref. [2]. There the incident angle is important for the loudness because the HRTF is involved.

### (4-2). Time window for a 0.05ms rectangular pulse

We learnt that two rectangular pulses of 0.05ms are heard as the same loudness at the time interval of 3.5-3.8ms [1]. It means that the time window for non-correlated two pulses is finished to have integration. This must be the shortest time window at hearing. It starts to be separated at 1.4 to 1.7ms but it is not yet done by the time window.

Even after this shortest time window, it is not long enough to understand the meaning of signals. They are not auto-correlated for that.

### (4-3). Time window after 40ms

The time window of 40ms is for the peripheral processing of a relatively short sound. A time window would be different depending on the content or the information of a sound because one tries to catch the meaning of the sound with auto-correlation. The central processing, like understanding of speech or music listening, starts.

When we listen to words or music, which has meaning, a time window depends on experience, information, time change, memory etc all will be related to it. After all, we need the multi-variable analysis. A time window would be different too if a sound is used to hear or not. The auto-correlation of a sound must be found and the time window for its loudness is found how much it is related to it, using the above mentioned methodology with the Thurston's scale.

The path difference with 40ms is 13.6m. For 50ms it's 17m. It is often referred this path difference to have the disturbance by an echo especially on speech.

**(4-4) Temporal aspect of a rectangular pulse of 0.05ms**

Looking back the experiments in the past with 0.05ms rectangular pulses, its temporal aspect seems as in the following.

For two rectangular pulses:

0ms ----Two pulses of the same amplitude are heard as one pulse with interference.

1.4ms ---Two positive pulses of the same amplitude start to be heard split.

1.7ms----Two pulses in positive and negative signs of the same amplitude start to be heard split.

3.5 — 3.8ms ----Each of two pulses of the same mplitude is heard same loud. slightly larger than that of a single pulse.

4 — 5ms ------ Two pulses are heard completely separated, but each loudness is still slightly larger.

50ms—80ms----- Two successive pulses were heard as three or more. Two non-correlated signals make Gestalt psychology. The inverse frequency of this range is 12—20Hz.

$\alpha$ wave has 8—13Hz, the lowest frequency of a pipe organ is 16Hz.

Time window for an impact noise:

40ms------Time window for an impact sound A singer at a choir does not like the delay from surrounding reflectors (Harold Marshall)

The discrimination time of 1—3ms by Hirsh [5] is referred to papers by Walach, Newman and Rosenzueing and it was found at different directions. On the other hand, our results in the above were obtained at the median plane.

The loudness increase of two separate pulses may not only be caused by the pure tone component of the time interval, but also by the integration in the time window owing to auto-correlation.

The rectangular pulse of 0.05ms is the fundamental quantity, and it is also an element to make non-correlation on our hearing system.

A sound field and the linear part of our hearing system have been solved referring to a rectangular pulse of 0.05ms. Accordingly, getting out a somewhat confused frequency expression, the acoustical linear phenomena were properly arranged and grasped clearly.

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