The transient response of human hearing system

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The transient response of our hearing system to the loudness of a rectangular pulse with a width of 0.05 ms was determined by the paired loudness comparison of two successive pulses with a varying time interval between them to that of a single pulse. The transient response was predicted to go a negative after an initial positive rise. The interference part of the transient consisting of a steep positive rise followed by a negative reaction was determined, and the loudness increase supposed to be due to the predominant pure tone spectrum caused by a time interval was also found. In the region from 50 to 80 ms of time interval, what was heard elsewhere as two separate tones was heard as three connected pulses.

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1. INTRODUCTION

The sound reflection from a rigid plane panel with limited dimension has a specular reflection followed by negative boundary waves. The latter become larger as the panel becomes smaller.¹⁾ However, because of the time interval between them we cannot readily explain our experience that the loudness of the reflection from a small rigid panel appears less loud. In order to explain the experience, we have to introduce a transient response for our hearing system. As the system includes at least some elastic parts like, for instance, an eardrum, it is predicted that a rectangular pulse excitation will create a positive response followed by a negative one. The A weighting curve appropriates the equal loudness contours for pure tones, but since it doesn't contain phase information, we cannot obtain its inverse Fourier Transform and hence predict the transient response of our hearing system.

The transient response mentioned above was measured for a rectangular pulse of width 0.05 ms which was created by the technique of convolution with the inverse filter of the transfer function of the loud-speaker to correct for its distortion. The time interval between two positive pulses of the same

amplitude or a positive and a negative pulse was varied, and the loudness of pulse pair was established by finding the level of a single pulse to give the most similar loudness among five different single pulses. The one half of the loudness which was judged the same as that of two rectangular pulses decided a point on the transient in the previous paper.²⁾ The largest loudness of two pulses, however, does not occur at that point, but it does so in the largest loudness of the second pulse. Including this fact, a new transient response of our hearing system was obtained in this paper.

When the interval between two pulses was around 2 ms, they began to be heard separately. However, the loudness of them was larger than that of each and this was the same even if the second pulse was negative. In this range (2~140 ms), the loudness of two pulses was increased as a result of the pure tone components that could be heard resulting from the repetition interval of two pulses. The excess loudness in this range will be also shown.

Some of the test subjects noticed that in the interval range of around 50 to 80 ms, the sound changed from being two separately heard tones to sound as if it were three continuous pulses.

2. PRODUCING A RECTANGULAR PULSE BY THE CONVOLUTION OF THE INVERSE FILTER

A rectangular pulse of 0.05 ms in length was recorded on the PCM tape recorder as shown in Fig. 1(i). It was reproduced by the full range type loud-speaker in the anechoic chamber and picked up by a condensor microphone placed 1.2 m in front of the loud-speaker in order to measure the transfer function of the system. The inverse filter of this transfer function was then used in the loud-speaker circuit to produce a rectangular pulse at the receiving point 1.2 m in front of the loud-speaker. This was achieved by convolving the filter with a rectangular pulse on the desk top computer, the result then being converted to an analog signal, and recorded on the PCM recorder to be reproduced by the same loud-speaker (see Fig. 1(ii)). The signal was also convolved with a Hanning window to avoid problems with rise times. The final pulse shape used for the experiments is shown in Fig. 2(i) and its spectrum in Fig. 2(ii). The amplitude of the rectangular pulse used for each of a pulse pair was either 86 or 93 dB referred to the steady level of the piston-phone. The twelve male students used as subjects for the experiments were

Fig. 1 Obtaining a rectangular pulse wave.

Fig. 2 Reproduced rectangular pulses for testing.

tested by audiometry and proved to be audiologically normal.

3. MEASUREMENTS OF THE TRANSIENT RESPONSE OF HUMAN HEARING SYSTEM

Two successive rectangular pulses with the same fixed magnitude of either 86 or 93 dB and width 0.05 ms were generated 1.2 m directly in front of the subject. The loudness of the pulse pair was compared with a preceding single rectangular pulse having the same width of 0.05 ms (see Fig. 3) and the subject was asked to find the one among five comparison pulses with the 0.2 amplitude difference as shown in Fig. 3 that has the most similar loudness. In order to be used to the experiment, each subject had the same experiments twice, and the latter result is discussed here. Although these paired comparisons were carried out under both monaural and binaural listening conditions, they did not show any significant difference, therefore, only the experiments with binaural listening are reported here.

The loudness of the pulse pairs was determined for a range of time intervals between the pulses

Fig. 3 Pair comparison of loudness of two successive pulses to that of a preceding comparison pulse. 1.0 corresponds to an amplitude either 86 or 93 dB.

Fig. 4 The loudness of two successive pulses of 93 dB depending on their time interval. The ordinate shows a comparison pulse amplitude whose loudness is the same as that of a pulse pair. Solid lines show measured results and dotted ones show simulated results in Figs. 7 and 8.

and also for when the pulse signs were changed. Figure 4(i) and (ii) show the variation of loudness with the change of time interval, when the signs of two pulses were one positive and one negative, and

both positive, respectively. The ordinate in Fig. 4 shows a comparison pulse amplitude whose loudness is the same as that of the pulse pair and is called loudness magnitude in figures of this paper to distinguish from “loudness” (in sone) which has been historically used.

As the part labelled A in Fig. 4(i) shows, when a pulse pair consisting of a positive pulse followed by a negative one has its delay between them changed, the loudness rises rapidly from zero at no time interval to unity which corresponds to the loudness of each pulse of a pulse pair, i.e. in this case having a level of 93 dB. 2.0 in the ordinate shows the loudness of a single pulse of 99 dB. It is assumed here that the system does not have any resistive loss. Very little loudness increase is observed in the interval B. But in part C, there is a range from around 1.0 ms to 3.5 ms delay where the loudness rises significantly above unity. After 3.5 ms, the loudness gradually converges to unity.

For the case of two positive pulses (Fig. 4(ii)), their loudness begins from the loudness of twice amplitude at no time interval, decreases rapidly through the region E, and then converges to a value slightly above unity.

In this way, the two discrete pulse stimuli are heard not separately but as one stimulus in the early time interval. Each pulse stimulus causes a transient response and the two responses interfere with each other in this region.

However, subjects, in average, started to hear them as separated stimuli at around a time delay of 1.4 ms when two positive pulses were presented. When a positive pulse followed by a negative pulse was given, they did so at around 1.7 ms. They heard two pulses clearly separated at around 4.0 ms still with a small loudness increase compared with one pulse alone as shown in Fig. 4. In this case the subjects were still asked to judge the loudness of the two pulses together by selecting the comparison pulse which they perceived to have the same loudness as the pulse pair.

4. HYPOTHESIS OF TWO KINDS OF TRANSIENT RESPONSE

A positive sound pressure stimulus will increase the pressure in the ear. However, an ear drum, lymph liquid and etc. behave elastically and it must be expected that they yield a negative reaction after the positive stimulus is over. Besides, in the

transmission process of the nervous system an inhibition reaction in the time domain is also evident. After a transient response was assumed as shown in Fig. 5, the experimental results of Fig. 4 were used to predict a detailed response.

Since part A in Fig. 4(i) was caused by the interference between different signs of the rising part of the response, the thick rising part of the transient in Fig. 5(i) was obtained. The reason why the loudness in the part B was not increased we suspect is due to the fact that the transient response of the first pulse has started to decrease. The part C shows the existence of the negative reaction in the transient response i.e. addition of the negative components has occurred. Here, the unity in the negative of the second pulse response was added to the remaining negative response of the first pulse, and it became more than unity. Accordingly, the thick negative part of Fig. 5(i) is obtained by subtracting unity from the loudness in part C. In the last part, E, since the remaining positive transient of the first pulse and the largest loudness of unity of the second pulse were added, the thick positive part in Fig. 5(ii) was obtained after unity was subtracted from the loudness increase there.

Now, in addition to the interference response, we have to understand the reason why the loudness in parts D and F is more than unity. It is shown that there is a loudness increase with 2 pulses com-

Fig. 5 Loudness addition in the transients of two successive pulses of the same amplitude and its comparison with a preceding single comparison pulse. A thin solid curve shows a predicted transient response, a dotted line shows the added loudness of each pulse, and a thick solid segment shows a part which is obtained from the loudness of two pulses. The amplitude unity corresponds to either 86 or 93 dB.

Fig. 6 Two kinds of transient responses of interference and excessive loudness. The ordinate, loudness magnitude, shows a comparison pulse amplitude whose loudness is the same as that of a pulse pair.

pared with the loudness of one pulse alone independently of the sign of the second pulse. The increase in loudness was noticed to occur after the point at which the two pulses started to be heard separately, namely at around 1.4 ms in Fig. 4(i) and 1.7 ms in Fig. 4(ii). When heard separately, a tonal quality to the pulse pair is noticed resulting from the spectrum determined by the time interval between the pulses. It is suggested that the extra loudness is caused by these additional pure tone components.

Since such addition is assumed to start in the region B, and decreases similarly in the regions D and F, the excessive loudness in the region E is assumed to be produced in the same manner as the region B, and the prediction of this kind of loudness change, which we are referring to as the excessive loudness caused by a separation tone of two pulses, is shown in Fig. 6.

5. MEASURED RESULTS FOR THE TWO KINDS OF TRANSIENT RESPONSES

The transient response curve obtained in the interference region thus is shown in Fig. 7(i) and (ii), for the time domain and the frequency domain, respectively. The thick line shows the average of the responses of twelve male students, whilst the thin curves show the responses of individual students. The frequency spectrum with a thick line in Fig. 7(ii) shows the Fourier Transform of the averaged transient response in Fig. 7(i). The reason for the high sensitivity in the low frequency range is that

Fig. 7 The transient response of interference tested by 12 male students. The thick line shows the average of them.

a low pitch sound was stimulated by the higher components of the rectangular pulse. It should be noticed that in both the time and frequency domains, the fine structure of each student is lost by averaging.

The excessive loudness caused by the separation tone of two pulses referred to the particular time interval between them is shown in Fig. 8 for the amplitude of each pulse of a pulse pair 93 dB.

The averaged transient responses for 86 and 93

Fig. 8 Excessive loudness change related to the time interval of two pulses. A thin line shows the excessive loudness of each student and the thick line shows its average.

(i) time domain.

Fig. 9 Transient responses of interference for different amplitude of each pulse of a pulse pair. Continuous lines show the results for the amplitude 93 dB and dotted ones show those for the amplitude 86 dB.

dB are compared in Fig. 9. There are no major differences between them, though each amplitude of a pulse pair is different by 7 dB.

6. DISCUSSIONS

Measurements of the temporal responses of our hearing system to various kinds of click sounds or pulses have been carried out in the past. It is, however, very difficult to compare the results and conclude from them, because the wave forms of the stimuli were not precisely controlled. However, Hirsh³⁾ has divided the response time region of 1 to over 100 ms into three parts. The first is the range of 1 to 20 ms governed by the relatively peripheral physiological events, the second is the range 20 to 100 ms perceived in a gestalt pattern recognition manner as for the visual sensory system, and the last range, over 100 ms, is for the linguistic response. Teranishi⁴⁾ also distinguished three regions, though different from Hirsh's. The transient response of the interference in Fig. 7 is considered to include the head related transfer function, the elastic behavior of the eardrum and middle ear bones, the wave reaction of the lymph liquid and basilar membrane, where it takes 5 ms⁵⁾ for a wave

(i) time domain.

(ii) frequency domain.

Fig. 10 The comparison of the transient response of interference with the head related transfer function.

to travel from the oval window to the helicotrema, and maybe even a very initial part of the peripheral nerve system.

The frequency characteristic in Fig. 7(ii) is completely different from the equal loudness curve generated by pure tone comparisons (see I.S.O.). The reason is that low pitch sounds are excited by the rectangular pulse which has a wide frequency content. The transient response at the ear drum of an artificial head resulting from excitation with a rectangular pulse of 0.05 ms from the front is shown in Fig. 10(i) and (ii) with a dotted line, and it is compared with the averaged measured transient response in this experiment with a continuous line. It is interesting that the resonance caused by the external channel is smoothed on the loudness transient response. In other words, though a received signal has a pure tone component, it does not

resister at the cerebral cortex where the loudness is perceived. This might suggest that the parts of the cortex where a pure tone and a wideband sound are perceived are different. We have to consider also that the low pitch sound created by two pure tones does not beat with a pure tone of the same frequency. Since one of the purposes of this experiment was to find the ear's transient response to convolve with auditorium impulse responses for acoustical estimation of auditoria, the result here will be very useful.

Furthermore, it is very interesting that in the range 50 to 80 ms, eight of the students perceived the sound as being composed of three linked pulses. From about 3 to 4 ms up until this time range two pulses were clearly heard. The loudness of two pulses in this range was also asked to judge which single pulse loudness is most similar among five.

Fig. 11 The transient responses of interference and excessive loudness of a Polish male of 28 years old and Japanese male students. Solid lines show the ranges of 12 Japanese students; (A) transient response of interference and (B) excessive loudness.

The time interval between two pulses gives the main spectral component at 12 to 20 Hz. It maybe related with the alpha wave which gives subjective good feelings when in the range 8 to 13 Hz. The lowest fundamental frequency of the pipe organs is 16 Hz, which were said to have been used consciously by old classical music composers to make listners feel at home. Recently, the nerve cells which give direct pattern recognition for hands and faces⁶⁾ on the visual sensory system have been found (at the hypothalamus). This response maybe related to the gestalt perception in the hearing system as Hirsh points out.

After the above experiment a Polish male of 28 years old was asked to carry out similar paired comparisons in order to see if there is any racial influence on the transient response of loudness. He performed same experiments three times, and the result for the third trial is shown in Fig. 11 with a dotted line. When comparing with the results from the 12 Japanese students whose ranges are expressed in solid lines, it is evident that there are no major differences between them. However, the separation tone of the two pulses was heard in the time interval of over 100 ms which may be different from the 50 to 80 ms range shown by Japanese students.

Since the interference region is suspected mainly due to the elastic and wave reactions in the system, the transient response triggered by the first positive pulse and the first negative pusle must be slightly different from each other especially in the case of the eardrum contribution.

It will be interesting to compare the transient response of interference and the excessive loudness with the results from evoked potential and acoustic emission experiments.

7. CONCLUSIONS

The transient response of our hearing system has been measured with rectangular pulse excitation of width 0.05 ms which was produced by inverse filtering of the loud-speaker response in the digital pro-

cessing.

There are two kinds of transient responses in the hearing system; one which results from interference and the other from additional loudness related to the time interval between the two pulses of the stimulus. The frequency characteristics of the transient response of interference showed most sensitive in low frequency. It is suspected to be caused by low pitch sounds excited by higher frequency components of the rectangular pulse. Any major racial differences on the transient response were not found.

The pulses could be heard separately from around 1.4 ms delay for two positive pulses, and 1.7 ms for a positive and a negative pulse. After around 4 ms they were completely separately heard. When the time interval between two positive pulses was in the region 50 to 80 ms, the perception was changed to one of three linked pulses.

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REFERENCES

- 1) Y. Sakurai and K. Nagata, "Sound reflections of a rigid plane panel and of the 'live end' composed by those panels," *J. Acoust. Soc. Jpn. (E)* **2**, 5-14 (1981).
- 2) Y. Sakurai, "Transient response of human hearing system," *Proc. 12th ICA, Toronto*, B3-1 (1986).
- 3) I. J. Hirsh, "Temporal aspects of hearing," in *The Nervous System, Vol. III, Human Communication and Its Disorders*, E. L. Eagles, Ed. (Raven Press, New York, 1975), pp. 157-162.
- 4) R. Teranishi, "Temporal aspects in hearing perception," in *Handbook of Hearing*, S. Namba, Ed. (Nakanishiya, Kyoto, 1984), Chap. 7, pp. 276-319 (in Japanese).
- 5) H. Sakai, "Acoustical analysis of the chochlea," in *Hearing and Psychoacoustics*, H. Sakai, Ed. (Corona, Tokyo, 1980), Chap. 3, p. 18 (in Japanese).
- 6) A. Mikami and K. Kubota, "Nerve cells for hands and faces," *Kagaku-Ashahi*, 28-32 (Sept. 1986) (in Japanese).