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AUDIBILITY OF COMPLEX TONES ABOVE 20 KHZ

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ABSTRACT
Audibility of ultrasonic components contained in a harmonic complex tone were investigated. The level of the components varied adaptively and the maximum level investigated was 80 dB SPL / component. All subjects distinguished between sounds with and without ultrasounds only when the stimulus was presented through a single loudspeaker. When the stimulus was divided into six bands of frequencies and presented through 6 loudspeakers in order to reduce intermodulation distortions of loudspeakers, no subject could detect any ultrasounds. It was concluded that ultrasonic components that were inaudible as a single tone could not have significant influence on impression of complex sounds.

1 - INTRODUCTION
The audible area has been believed to range between 20 Hz and 20 kHz. It has been reported that the detection threshold for tonal stimuli starts to raise quite abruptly when the frequency of the tone exceeds about 15 kHz and it reaches 80 dB SPL at the frequency of 20 kHz [1], [2].
In the last decade, however, several groups of researchers have used complex sounds (pulse train, musical sounds, environmental sounds, etc.) as the stimuli and claimed that subjective impression of sounds could be significantly affected by addition of ultrasounds [3], [4], [5]. Possible influence of ultrasounds does not seem to be considered in the conventional minimum auditory field and equal loudness contours. If the ultrasonic components could have significant influence on impression of complex sounds, it might be necessary to reconsider the concept of the minimum auditory field and equal loudness contours.
If the ultrasounds could affect sound impression only when they were contained in complex sounds, it can be suspected that the influence is due to some non-linear interactions that take place somewhere between the sound source and the auditory cortex. They can occur in the air between the sound source and eardrums, and somewhere in the auditory system. They may also occur at the sound source including amplifiers and loudspeakers. If the interactions would occur in the air or in the auditory system, it may be at least practically appropriate to say that ultrasounds are audible. If they would occur at the sound source, they were merely the experimental artifact and should have been eliminated by somehow. In the previous studies, however, possible effects caused by non-linear characteristics of the equipment were not sufficiently discussed. In the present study, not only the audibility of ultrasounds but also the effects possibly caused by experimental artifacts were investigated.

2 - METHOD

2.1 - Stimuli
A harmonic complex tone consisted of only odd number harmonics was used as the stimulus. Its fundamental frequency (f0) was 2 kHz. The sound spectrogram of the stimuli is shown in Fig. 1. The lower 5 components that were the fundamental, 3rd, 5th, 7th and 9th harmonics were defined as non-target components and the higher 5 components that were the 11th, 13th, 15th, 17th and 19th harmonics were defined as target components. Frequency of the highest harmonics was 38 kHz. The duration of the stimulus was 2000 ms including linear onset and offset ramps of 100 ms each.
The question was if subjects could discriminate between stimuli with and without the target components. In order to make discrimination easy, only the target components were modulated by a sinusoid of 2 Hz.

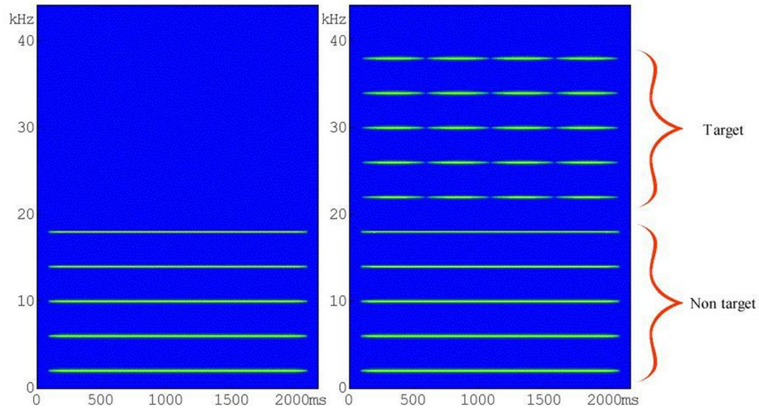

Figure 1: Sound spectrogram of the stimuli.

If the ultrasonic components were audible, subjects would perceive fluctuation of 2 Hz only when there were the target components. The level of the non-target components was fixed at 60 dB SPL while that of the target components varied adaptively so that the discrimination threshold was estimated.
In order to investigate effects caused by intermodulation distortions of loudspeakers, the discrimination threshold was estimated in two different conditions. The one was called the single-loudspeaker condition and the other was the six-loudspeaker condition. These conditions are illustrated in Fig. 2. Only one loudspeaker (loudspeaker A) was used to present stimuli in the single-loudspeaker condition. In this case, addition of the target components increased amplitude of a total input to the loudspeaker and might induce intermodulation distortions of the loudspeaker.
Six loudspeakers were used in the other condition. The non-target components were presented through the first loudspeaker and each target component was presented through each of the other 5 loudspeakers (loudspeaker B, C, D, E and F), so that no intermodulation would be induced by addition of the target components.

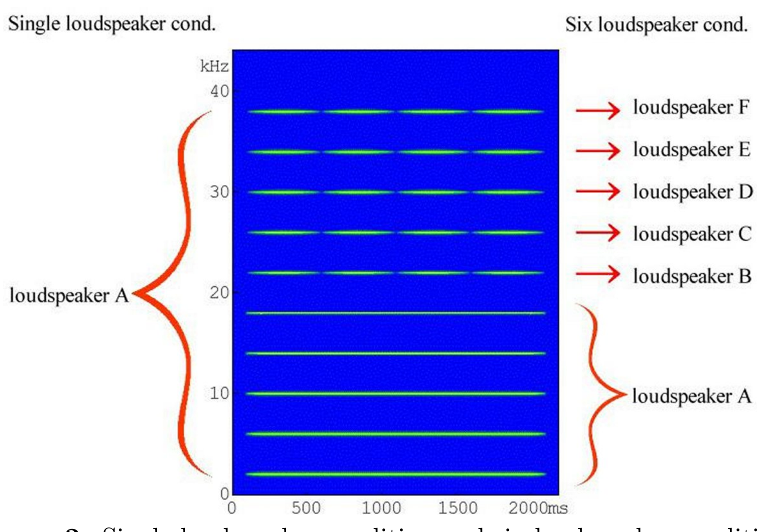

Figure 2: Single-loudspeaker condition and six-loudspeaker condition.

2.2 - Equipment and subjects

Six loudspeakers were arranged in 2 vertical and 3 horizontal rows at the distance of 150 cm from the listening point as illustrated in Fig. 3. All of them were Victor SX-V05. All stimuli were synthesized at a sampling rate of 88.2 kHz and 16-bit resolution. They were generated by 3 stereo D/A converters (Sek'd ADDA2496S). Three stereo amplifiers were used, two of which were Luxman L-507s and the other one was Accuphase E-406.
Ten males and 3 females participated as the subjects. All of them were either undergraduate or graduate students and had normal hearing. Their ages ranged between 19 and 26 years. They were paid for their

participation. None of them could detect any stimulus above 22 kHz when it was presented as a single tone and its level did not exceed 85 dB SPL.

2.3 - Procedure

A three-interval two-alternative forced-choice paradigm was adopted with a three-down, one-up transformed up-down method that tracked 79.4% correct [6]. The reference stimulus was presented in the first interval and was followed by two test stimuli. The reference and one of the test stimuli always contained the target components while the other test stimulus did not. There were silent intervals of 300 ms between each stimulus.

The subjects were required to judge which test stimulus was the same as the reference stimulus. A visual feedback was given immediately after every response. The level of the target components was 72 dB SPL / component at the beginning of each run. It decreased after three consecutive correct responses and increased after every wrong response. A single run consisted of 10 reversals. The discrimination threshold was defined as the mean level at the last 6 reversals. The minimum step size was 1 dB. If the level of the target components exceeded 80 dB SPL before 10 reversals were completed, the run automatically terminated and no estimation was made.

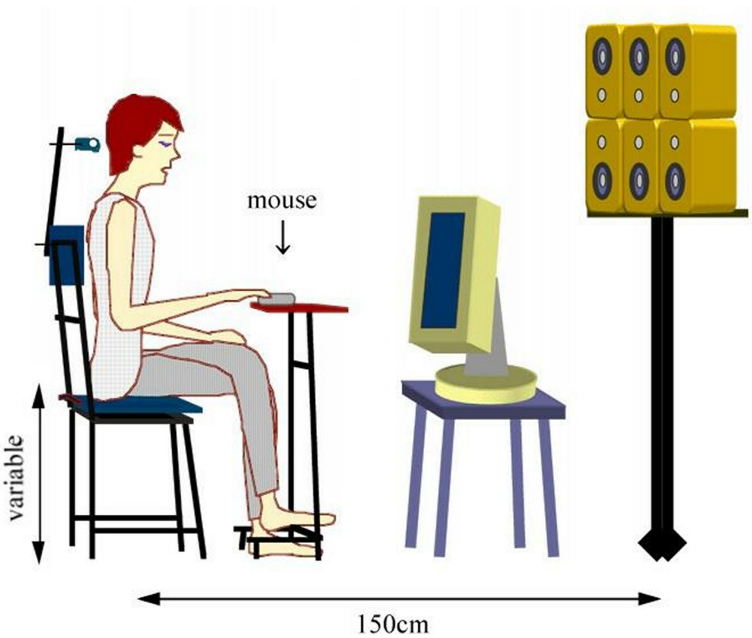

Figure 3: Loudspeakers and the subject.

3 - RESULTS AND DISCUSSION

The discrimination threshold in the present experiment was the level at which 79.4% correct response was achieved. The discrimination threshold did not exceed 70 dB SPL in the single-loudspeaker condition. The average threshold in this condition was 65.76 dB SPL while no threshold below 80 dB SPL was obtained in the 6-loudspeaker condition. In order to investigate why addition of the target components had significant influence on the sound impression only in the single-loudspeaker condition, the stimuli were acoustically analyzed via a 1/2 inch microphone (B&K 4133).

Fig. 4 shows the power-spectrum of the stimulus without the target components. Fig. 5 and Fig. 6 show the stimuli with the target components in the single-loudspeaker condition and the 6-loudspeaker condition, respectively. The even number harmonics were observed even in the audible area (indicated by an arrow) only in the single-loudspeaker condition (Fig. 4). They seem to be intermodulation distortions of the loudspeaker because they were not observed in the 6-loudspeaker condition (Fig. 5).

There have been controversy about audibility of ultrasounds. Muraoka et al. [7] used musical sounds and reported that only a few out of 176 subjects distinguished the sounds with and without components above 20 kHz. Several recent studies, on the other hand, revealed that the ultrasonic components would significantly affect the sound impression of the normal listeners. In the present study, audibility of the components above 22 kHz was investigated under two conditions in order to observe effects caused by the experimental artifacts.

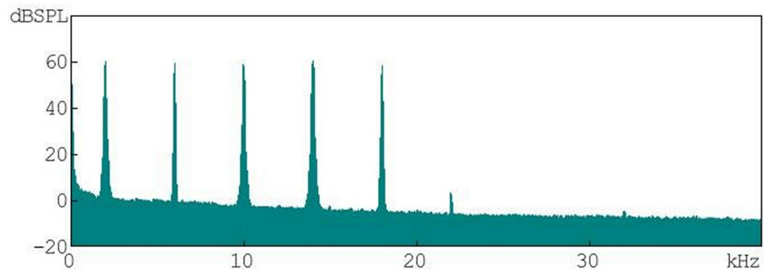

Figure 4: Power-spectrum of the stimuli without target components.

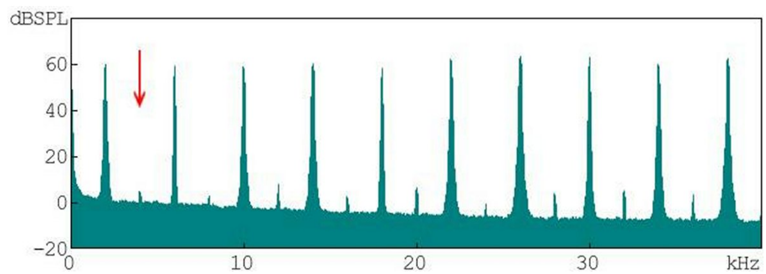

Figure 5: Stimuli with the target components in the single-loudspeaker condition.

If the components above 22 kHz were audible, the subjects should have discriminated the stimuli with and without the target components in both experimental conditions. However, they discriminated only in the single-loudspeaker condition where the intermodulation distortions were induced by addition of the target components. The linearity of the loudspeaker used here was about 50 dB when the input was 1 W. This value is average or even better than average consumer loudspeakers [8]. It was indicated from the results that the non-linear interaction of ultrasounds in the air or in the auditory system was, if any, not so much as that in the average loudspeakers as far as the level of the signal did not exceed 80 dB SPL.

Components above 22 kHz did not significantly affect the impression of a complex tone when the experimental artifacts were adequately eliminated in the present experiment. In this study, however, only a synthesized complex tone was used and no data have been available for musical sounds nor natural environmental sounds. It requires further investigations in which great care has to be taken to remove artifacts due to non-linear characteristics of the equipment especially the loudspeakers.

ACKNOWLEDGEMENTS

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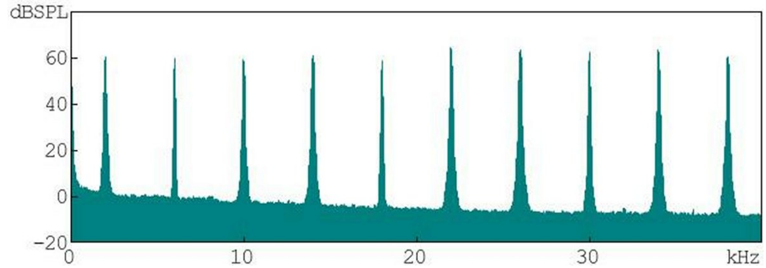

Figure 6: Stimuli with the target components in the 6-loudspeaker condition.

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