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Perceptual discrimination of very high frequency components in wide frequency range musical sound

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ABSTRACT

Subjective evaluation tests on perceptual discrimination between musical sounds with and without very high frequency (above 20 kHz) components were conducted. To make a precise evaluation, the test system was designed to exclude any influence from very high frequency components in the audible frequency range. Moreover, a newly developed very wide frequency range microphone was used to record various sound stimuli that contained enough components in the very high frequency range. Tests showed that the subjects could discriminate between musical sounds with and without very high frequency components. This paper describes these subjective evaluations in terms of reproducing such very high frequency components in musical sound.

1. Introduction

It is generally accepted that the frequency bandwidth of human hearing by air conduction does not far exceed 20 kHz. However, high sampling digital audio conversion and storage such as SACD and DVD-Audio have amplitude responses of close to 100 kHz, and frequency components far exceeding the range of the auditory band (below 20 kHz) can be recorded and reproduced. Studies on the bandwidth of human hearing are important for defining the frequency bandwidth for sound recordings and for developing electro-acoustic transducers (such as microphones and loudspeakers). Broadcasters also need to study this issue for the development of next-generation broadcasting systems and the definition of the recording format of audio archives.

There have been several studies on the frequency range up to 15 kHz [1–3]. Fausti et al. [4] measured the auditory function from 8 to 20 kHz and compared their results with previous studies. They showed that the hearing threshold for tonal stimuli rises abruptly from 16 kHz. Subsequent studies were carried out to determine the sampling frequency of digital audio systems. Plenge et al. [5] conducted subjective evaluation tests with 43 subjects using a sequence of two impulses opposite in polarity as the test signal, and concluded that a 15 kHz transmission bandwidth is enough. Tanabe et al. [6] investigated the bandwidth of hearing by using a synthetic stimulus containing many high frequency components and a 40 kHz bandwidth reproduction system. They reported that a few subjects could distinguish signals with and without over 20 kHz components. However, almost all subjects could not distinguish a 19 kHz high-cut signal from the full frequency range sound. Hence, a 22 kHz bandwidth was deemed sufficient for high-quality sound transmission. Muraoka et al. [7] tested 176 subjects using musical sounds and a sweep tone, and reached the conclusion that an upper band limit of 20 kHz is high enough for a professional audio system's transmission. Thus, the upper limit of the frequency range in conventional digital audio formats such as CD, DAT, and digital audio broadcasting is typically set at about 20 kHz.

For the last decade or more, studies have reported on the possibility that "inaudible" very high frequency components above 20 kHz in non-stationary sound may affect the auditory sense or brain activity. Oohashi et al. reported that high frequency components above 22 or 26 kHz in the gamelan music of Bali affect the perception of audible sound, electrical activity in the brain, and regional cerebral blood flow [8,9]. It was also reported that these affections could not be observed when only the audible band or very high frequency band was reproduced. Matsushima et al. [10] reported that high frequency components above 20 kHz containing the natural environment sound of a forest affect the psychological sound evaluation and content of brain waves. Yoshikawa et al. [11] conducted an experiment using 20 and 40 kHz bandwidth pulse train signals, and concluded that a wider frequency range of the audio system improves the perceptual time-axis resolution. On the other hand, some papers reported no significant differences between the effects of audio signals with and without very high frequency components [12–14].

If such inaudible very high frequency components affect the perception of sound, it is important to isolate two factors of the affection to the auditory sense. One is the very high frequency

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components themselves and the other is the changes in the auditory band caused by reproduction of the very high frequency components. One of the latter factors is the non-linear distortion of the experiment system [15]. Non-linear distortion might be generated by non-linearity of (a) the recording system, (b) reproduction system, and (c) sound wave transmission. Non-linear distortion of type (a) does not affect the results of the above-mentioned experiences because it is contained in the sound stimulus and is not affected by the means of reproduction. Regarding the type (b) distortion, Ashihara [16] and Griesinger [17] suggested that non-linear distortion in the auditory band generated by a loudspeaker or amplifier affects auditory perception when there are complex tones with and without very high frequency component. The distortion of type (c) possibly occurs when the reproduction has high pressure levels [18,19].

In the previous studies reporting that very high frequency sound affects hearing [8–11], however, the influence of such non-linear distortion was not quantitatively analyzed. In the current study, the non-linear distortion of the experiment's audio system was measured to isolate the non-linear distortion and the very high frequency components above 20 kHz.

While previous studies have used DVD-Audio or SACD releases as sound stimuli, this study used originally recorded wide frequency range sound stimuli for control of the sound quality and very high frequency component level.

We carried out two experiments. Experiment 1 was a primary test aimed at assessing whether very high frequency components in musical sound influence human hearing or not and whether the influence depends on subject and stimulus or not. Hence, this experiment featured various sound stimuli and subjects [14]. After considering the results of experiment 1 and previous studies, we modified the experimental design and carried out a more elaborate experiment with a newly recorded stimulus [20].

This paper is organized as follows: Section 2 provides details of the experimental system. Section 3 describes the first subjective evaluation experiment and its supplementary test. Section 4 describes the second evaluation experiment, the measurement of the subjects' hearing threshold, and the non-linear distortion of the loudspeaker. Section 5 concludes this paper with a discussion.

2. Experimental system

2.1. System diagram

To make a strict subjective evaluation test, the sound reproduction system was designed to exclude any leakage or influence from very high frequency components in the audible frequency range. The test system consisted of two completely independent sound reproduction systems, one for the audible frequency band, and the other for the very high frequency band, as shown in Fig. 1. Each system had independent sound equipment, namely D/A converters, power amplifiers, loudspeakers, and power supply units.

The sound source used as stimuli for the subjective evaluation tests also consisted of two frequency bands (below and above 21 kHz) that were divided by 1024-tap FIR digital low-pass and high-pass filters, which had very sharp roll-off characteristics, as shown in Fig. 2. The cut-off frequency for the low-pass filter was 20 kHz, and that of the high-pass filter was 22 kHz. The transition bandwidth of both filters was 1 kHz, and the rejection level was set at over 90 dB. Accordingly, the sound sources were divided almost perfectly into an audible frequency band (below 21 kHz) and a very high frequency band (above 21 kHz) without any overlap in the frequency domain, and each frequency band was recorded independently on a different track of a digital audio workstation. Of course, these two different frequency bands were precisely synchronized. During the subjective evaluation tests, each frequency band was reproduced from different tracks and amplified independently.

A mute unit was inserted between the amplifier and D/A converter of the very high frequency band. Throughout the evaluation tests, the sound of the audible frequency band was always reproduced and the sound of the very high frequency band was muted or reproduced according to the test sequence. As this method excluded any influence of non-linear distortion from very high frequency band components within the audible frequency band, it was possible to make an absolute comparison between sounds with and without very high frequency components. The digital equipment in the test system was operated at a sampling rate of 192 kHz and with 24-bit resolution.

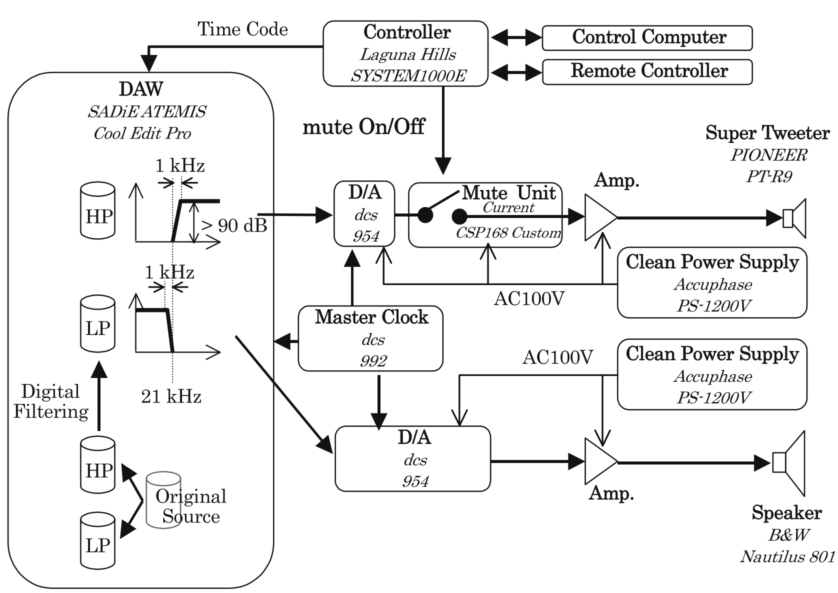

Fig. 1. Diagram of the experimental system. The test system consisted of two independent reproduction systems: one for the audible frequency band (<21 kHz) and the other for the very high frequency band (>21 kHz), to exclude any leakage or influence from very high frequency components in the audible frequency range.