

## Bone-conducted Ultrasonic Hearing Aid for the Profoundly Deaf: Development of a Downsized Digital Prototype

重度難聴者のための骨導超音波補聴器：デジタル試作器の開発

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### 1. Introduction

Bone-conducted ultrasound (BCU) can be experienced as sound, not only by normal hearing subjects but also by the severely hearing-impaired. We have proven the BCU perception objectively by measuring magnetoencephalography, and developed a BCU hearing aid (BCUHA) for the profoundly deaf [1]. Remarkable results have already been achieved; enabling 30 percent of the profoundly deaf trial subjects to recognize simple words and half of them to perceive some sort of sound. These results suggested its practicability, however, further development and improvements remain essential. Especially, the existing prototype is relatively heavy in weight and large in size, because the main components consist of analog circuits. Additionally, it was difficult to modify or add new functions to the signal processing components. Digital processing unit is essential both to downsize and to implement advanced and flexible signal processing.

In this study, a prototype using a newly created digital processing unit was developed to achieve downsizing enough to tote and advanced and flexible signal processing. Additionally, new amplitude-modulation (AM) methods were installed and their intelligibilities and sound qualities were evaluated.

### 2. Development of a downsized digital prototype

#### 2.1 Development of a small-sized digital processing unit

The BCUHA needs a real-time signal-processing unit that includes microphone amplifiers, power amplifiers for the vibration output, an output limiter, and a gain controller. Also, the unit needs to contain a power supply and to be compact enough. A small digital processing unit was developed (Fig. 1). The unit consists of the following components:

- Microphone: 4 ch
- Sound signal amplifier:  $-34.5 \sim +12$  dB, 1.5-dB step programmable
- Digital sound signal processor: 1 processor (TMS320C6713, Texas Instruments Co., 200 MHz, 1.7 GFlops), 2 AD/ DA converters (12 MHz), 1 MB RAM, and 1 MB Flash ROM, that implements:
  - Speech-sound modification
  - Carrier generation ( $27 \pm 5$  kHz)
  - Three types of AM (see Sec. 2.2)
  - Automatic carrier ON/OFF control
  - Modulation-depth control
  - Calibration-signal generation
  - Equalization of input signal
- Output amplifier: 1.2 W (max.),  $-73.0 \sim +6$  dB, 1.0-dB step programmable
- Output amplitude limiter: 35 dB above the user threshold
- Vibrator: A piezoelectric device with a resonance frequency of 40 kHz.
- Headgear: Attaches the vibrator to the mastoid with pressure of about 5 N
- Power supply: 2 batteries (size AA) or external DC supply
- Display unit: LCD panel ( $128 \times 64$  pixel, BW)

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The maximum sampling frequency of the total system is 96 kHz.

#### 2.2 Implementation of three types of amplitude modulation

Three AM methods were used in the new prototype. These methods are expressed as follows, where  $A$ ,  $s(t)$ ,  $fc(t)$ , and  $m$  represent a constant, the modulator signal (speech), a carrier signal, and the modulation-depth, respectively.

- Double-sideband with transmitted carrier (DSB-TC):  $f(t) = A(1 + m s(t)) \times fc(t)$  (1)

- DSB with suppressed carrier (DSB-SC):  $f(t) = A(m s(t)) \times fc(t)$  (2)

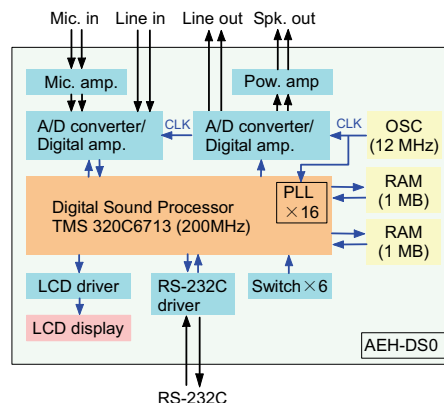


Fig. 1. Block diagram of the small-sized digital signal processing unit.

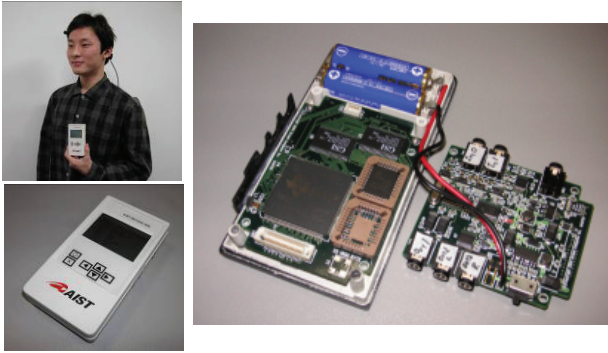


Fig. 2. Newly developed BCUHA prototype using the small-sized digital processing unit.

The DSB-SC method has an advantage in terms of power savings.

3) Transposed modulation [2]:

$$f(t) = A(m s_{ip}(t)) \times f_c(t) \quad (3)$$

where  $s_{ip}(t)$  represents a half-wave-rectified and low-pass-filtered modulator signal. Transposed-BCU speech is essentially distorted to some degree because of ectification. However, as the modulation depth rises, the high-pitched tone due to the ultrasonic carrier is suppressed.

### 2.3 Assembly of a down-sized BCUHA

A downsized BCUHA prototype was developed using the newly created digital processing unit. Fig. 2 illustrates the new BCUHA prototype, which is compact enough to tote (size: 64×118×22 mm, weight: 117 g). Some parameters (carrier frequency, carrier amplitude, input signal amplitude, modulation depth, output signal amplitude) can be set on the liquid crystal display. Other parameters can be set from a personal computer via an RS-232C interface.

## 3. Evaluation of the new prototype

Psychoacoustical measurements were done to test the utility of the newly installed AM components.

### 3.1 Intelligibility

Word intelligibility for 4-mora Japanese word were investigated. Three AM methods were used: DSB-TC, DSB-SC, and transposed (low-pass filtered at 8 kHz). For all stimuli, the carrier signal  $f_c(t)$  was a 30-kHz sinusoid, and the modulation depth  $m$  was adjusted for each word to avoid over-modulation. In the results, DSB-SC speech was less intelligible than other BCU speech ( $p < 0.001$ ), whereas no significant difference was observed between DSB-TC and transposed speech.

### 3.2 Evaluation of sound quality

After each session of the word-intelligibility test, the subjective impression of the sound was examined using a questionnaire [26]. Subjects were asked to rate the followings on three-point scales:

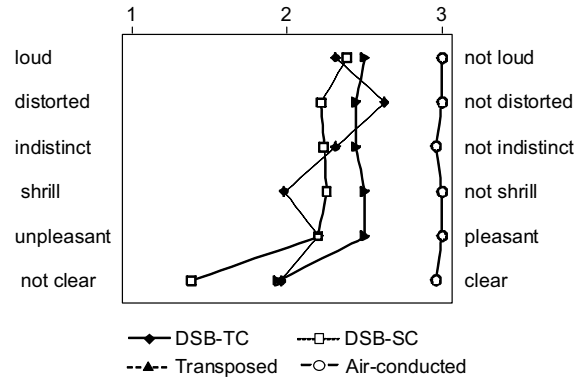


Fig. 3. Results of the questionnaire for listening with hearing aids.

(1) Loudness, (2) Distortion, (3) Indistinctness, (4) Shrillness, (5) Unpleasantness, (6) Clarity.

Fig. 3 shows the result. The effect of the stimulus type on answers to all questions in the questionnaire was observed ( $p < 0.001$ ). The DSB-SC stimulus is less clear than other BCU stimuli, and more distorted than the DSB-TC ( $p < 0.001$ ). The transposed stimulus is more pleasant than other BCU stimuli ( $p < 0.005$ ) and less shrill than the DSB-TC stimulus ( $p < 0.05$ ). The results indicated that the DSB-SC performed less well than other AM methods, and some differences were also observed between the DSB-TC and transposed speech. Transposed speech was less shrill and more pleasant than DSB-TC speech. The sound quality of transposed speech is considered to be closer than that of DSB-TC to the sound quality of AC speech.

## 4. Conclusion

A BCUHA prototype using a newly created small digital processing unit was developed. This achieved downsizing and advanced and flexible signal processing. Further, new AM methods were installed and evaluated to obtain better articulation and comfortable hearing. Psychoacoustical tests showed that the transposed modulation has some advantages in terms of sound quality over other AM methods.

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