Amplitude variation of bone-conducted speech compared with air-conducted speech

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Abstract: We explore the phenomenon of amplitude variation of bone-conducted (BC) speech compared with that of air-conducted (AC) speech. During vocalization, in addition to the AC components emitted through the mouth, vibrations travel through the vocal tract wall and the skull bone before they arrive at the cochlea. A bone-conductive microphone placed on the talker’s head can partly capture these vibrations and convert them to BC speech signals. The amplitude of this BC speech is influenced by the mechanical properties of the bone-conduction pathways. This influence is related to the vocal tract shape, which determines the resonances of the vocal tract filter. Referring to these resonances as formants of AC speech, we can describe the amplitude variation of BC speech with respect to the location of the formants of AC speech. In this work, the amplitude variation of BC speech of Japanese vowels, CV (consonant–vowel) syllables, and long utterances have been investigated in terms of the locations of the first two formants of AC speech. Our observation suggests that when the first formant is very low with a higher second formant, the relative amplitude of BC speech is amplified. On the other hand, a relatively high first formant and lower second formant of AC speech cause a reduction in the relative BC amplitude.

Keywords: Bone-conducted speech, Air-conducted speech, Vocal tract filter, Formant, Bone-conduction pathway

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1. INTRODUCTION

When we speak, the voice signal is transmitted to the cochlea mainly via two different pathways. Air conduction is the normal path of the sound emitted from the mouth and transmitted through air. Bone-conducted components, on the other hand, consist of vibrations transmitted directly from the oral cavity to the cochlea via the vocal tract wall and skull bone [1–3]. Depending on its placement, a bone-conductive microphone (BCM) equipped with a vibration sensor can decipher these vibrations to some extent and convert them to an electrical signal, which is referred to as BC speech. Unlike air conduction, bone conduction is not affected by ambient disturbances. This apparent advantage has led many researchers to study BC speech in cases of severe noisy conditions where the performance of conventional speech processing systems substantially deteriorates [4].

Although there have been a few decades of research on hearing by bone conduction, studies of its application to speech communication in a noisy environment have just begun to emerge. A major concern with BC speech is its lower intelligibility owing to weaker higher-frequency components [5,6]. Most of the recent works, therefore, have concentrated on enhancing the intelligibility of BC speech [4,7]. A number of studies have also been conducted to identify the most appropriate location for detecting bone vibrations [5,8,9]. BC speech has also been shown to provide an accurate estimate of the pitch frequency [10]. In an attempt to find a transfer function for BC transducers, a BC vs. AC comparison of amplitude and phase shifts was previously carried out [11], where listeners canceled AC and BC tone pairs by a method of adjustment at three frequencies (500, 3,150, and 8,000 Hz). However, alignment of amplitude and phase shifts does not enhance the intelligibility of BC speech. In summary, although many algorithms have been proposed to study and improve the suitability of BC speech, the inherent
mechanism of bone conduction is still not well understood. In this article, we attempt to study the time-domain amplitude variation of BC speech compared with that of AC speech depending on the spectral properties (particularly the first and second formants) of the latter [12]. Using the amplitude variation of BC speech, we can model the first and second formant ($F_1$ and $F_2$) tracks of AC speech. The adjustment of even only the $F_1$ (and optionally $F_2$) tracks of BC speech to that of AC speech eventually enhances the intelligibility of BC speech; this will be useful for speech processing in a noisy environment. Previously, we attempted such frequency correction by an analysis-synthesis method [13].

The vocal cord signal after being spectrally shaped by the vocal tract filter partly travels as vibrations through the skull bone. The mechanical impedance of the bone conduction pathways, which mainly comprise the skull bone and skin, influences the amplitude and frequency contents of BC speech. This influence is related to the formant frequencies of AC speech. As reported in this paper, a study was conducted using the formant locations of Japanese vowels, CV syllables, and long natural utterances spoken by male and female speakers. We found that the amplitude of BC speech is highly sensitive to the locations of the first formant of AC speech. In particular, a voice with a very low first formant and higher second formant is more suitable for bone conduction in terms of the time-domain amplitude and leads to the amplification of the relative BC amplitude compared with that of AC speech. On the other hand, reduction of the relative BC amplitude takes place for a higher first formant and lower second formant. The phenomenon was studied primarily using a commercially available BCM (Temco HG-17). A flat microphone response was then theoretically simulated and applied to show the results in the case of microphone independence.

The rest of the paper is organized as follows. In Sect. 2, we present the modeling of AC and BC speech. In Sect. 3, the amplitude behavior of BC signals of separate vowel sounds, CV sounds, and natural utterances recorded by the Temco HG-17 microphone are described. In Sect. 4, we discuss the analysis of the amplitude behavior of BC speech that was simulated to be free of any particular microphone response.

### 2. MODELING AC AND BC SPEECH

In the source-filter model of speech production, the vocal tract output of a voice is modeled as

$$x(t) = u(t) * v(t),$$

where $u(t)$ and $v(t)$ represent the corresponding glottal waveform and vocal tract impulse response, respectively. The operator $*$ stands for convolution. For voiced sound, the source is quasi-periodic puffs of air flowing through the glottis vibrating at a certain fundamental frequency. The vocal tract impulse response is determined by the shape of the vocal tract, which, in turn, determines its resonances. Stevens [14] developed rules for mapping changes in the vocal tract shape to formant transitions on the basis of physical principles.

As mentioned earlier, during vocalization, the AC component is emitted from the mouth. Thus, including the effect of lip radiation $r(t)$, AC speech can be defined using Eq. (1) as

$$s_{ac}(t) = x(t) * r(t).$$

BC speech, on the other hand, can be modeled as

$$s_{bc}(t) = \hat{x}(t) * b(t) * k(t) * m(t),$$

where $b(t)$, $k(t)$, and $m(t)$ represent skull bone, skin, and microphone impulse responses, respectively, and $\hat{x}(t)$ is the approximated version of $x(t)$ transmitted to the vocal tract wall. In AC speech, lip radiation acts as a difference filter (with transfer function $1 - z^{-1}$) that actually does not change the formant characteristics of speech. However, as indicated by Eq. (3), compared with AC speech $s_{ac}(t)$, BC speech $s_{bc}(t)$ is influenced by the bone and skin properties. When sound vibrations propagate through the skull bone, they need to overcome the bone’s opposition to transfer energy caused by its impedance. Two impedance measures, frequently referred to as skull impedance and skin impedance, are important in bone conduction. Several investigators have attempted to measure the impedance of the skull with and without the skin present [15]. Although the coupling between the skull and the skin is not yet well understood, it has a certain effect on the amplitude of BC speech $s_{bc}(t)$. Both types of impedance have been considered to be affected on the basis of the frequency characteristics of the input [i.e., $x(t)$ in this case] [15,16]. This suggests that the amplitude variation of BC speech $s_{bc}(t)$ is related to the spectral properties of AC speech $s_{ac}(t)$. In this study, we attempt to explain the amplitude variation of $s_{bc}(t)$ in terms of the formants estimated from $s_{ac}(t)$. Furthermore, unlike the air-boom microphone, the response of the BCM is not flat, which may have an additional effect on the recorded speech. The amplitude variation of BC speech is reported here with or without the microphone’s effect taken into account.

### 3. AMPLITUDE BEHAVIOUR OF BC SPEECH STUDIED USING TEMCO HG-17 MICROPHONE

According to Eq. (3), the combined effect of $b(t)$, $k(t)$, and $m(t)$ modifies the amplitude of AC speech and yields BC speech. Simultaneously recorded AC and BC speech are used to investigate the variation in the relative...
amplitude of BC speech with respect to the AC counterpart. Speech is initially recorded at a rate of 48 kHz then downsampled to a rate of 8 kHz for processing. A standard Panasonic RP-VK25 microphone is used for recording AC speech and a Temco HG-17 microphone is used for capturing BC speech with the vibration sensor positioned at the top of the head (vertex). The distance between the lips and the AC microphone is fixed so that the variation in the amplitude of AC speech is not due to the variation of the microphone distance. The AC and BC microphones are connected to two input channels of an amplifier, where the output channel is connected to a computer. AC and BC parts of the signal are then separated by interleaving the speech data received from the amplifier. The data are not corrected before processing. Since the sensor types and hardware (e.g., amplifiers) used for capturing AC and BC speeches are different, the sequence of utterances is normalized so that the maximum amplitude in the utterance is set to $+/-1$.

All the speech materials were collected from native Japanese speakers (four males and four females) ranging in age from 23 to 24 years. There are five pure vowels (monothongs) and seventeen consonant phonemes in Japanese, compared with a total of twenty vowels and twenty-four consonants in English [17]. Japanese language is based on syllables rather than a phonetic system. The vowel sounds occur with a number of consonants where the syllabic order is generally consonant plus vowel (i.e., CV) or vowel alone. We investigate the amplitude behavior of vowel sounds, CV syllables, and natural utterances spoken by male and female speakers.

### 3.1. Experiments on Vowel Sounds

Preliminary experiments have been conducted on the five Japanese vowel sounds. AC and BC signals of /a/, /i/, /u/, /e/, and /o/ spoken by a male speaker are shown in Fig. 1.

As can be seen in Fig. 1, the relative amplitude of BC speech /a/ is reduced and those of /i/ and /u/ are amplified compared with the AC counterparts. In close vowels, such as /i/ and /u/, the tongue is positioned high in the mouth, whereas in open vowels, such as /a/, the tongue is positioned low in the mouth. The more closed a vowel, the lower the $F_1$ value [18,19]. Autoregressive spectra and periodograms estimated from the AC signals of five consecutive 30 ms frames of each vowel sound in Fig. 1 are shown in Fig. 2. As seen in Fig. 2, the first formant of /i/ and /u/ occurs roughly at 322 Hz and 331 Hz, respectively. From our observation, when $F_1$ of the AC signal is very low, as in the case of the close vowels /i/ and /u/, the relative BC amplitude is notably amplified compared with that of AC speech. In contrast, the more open a vowel, the higher the $F_1$ value. As seen in Fig. 2, the first formant of /a/ occurs at 725 Hz. When $F_1$ of the AC signal is higher, as in the case of open vowel /a/, the relative BC amplitude is reduced. Moreover, in front vowels, such as /i/, the tongue is positioned forward in the mouth, whereas in back vowels, such as /u/, the tongue is positioned towards the back of the mouth. The fronter a vowel, the higher the $F_2$ value, and the more retracted a vowel, the lower the $F_2$ value. When the $F_2$ value of the AC signal is substantially higher, the relative BC amplitude of a close vowel is more amplified. For example, the relative BC amplitude of /i/ with higher $F_2$ is more amplified than that of /u/ with lower $F_2$ value. In addition, both /e/ and /o/ are mid-vowels (where the tongue is positioned between high and low in the mouth), but /e/ is located fronter than /o/. The relative BC amplitude of front vowel /e/ is therefore less reduced than that of back vowel /o/. This is evident in the short-time magnitude ratio.

![Fig. 1](image1.png)  
**Fig. 1** Relative amplitudes of five vowel sounds spoken by male speaker MA1. (a) AC speech. (b) BC speech.

![Fig. 2](image2.png)  
**Fig. 2** Spectra of the five vowel sounds in Fig. 1 spoken by a male speaker.
of BC and AC speech, as shown in Fig. 3, where the scores indicate the degree of amplification (> 1) or reduction (< 1). This plot is produced using the BC and AC speech signals given in Fig. 1. Here, the short-time magnitude ratio is computed as

$$\frac{P}{N} = \frac{\sum_{n=0}^{N-1} |s_{bc}(n)|}{\sum_{n=0}^{N-1} |s_{ac}(n)|}$$

where $N = 240$ is the frame length, and $s_{bc}(n)$ and $s_{ac}(n)$ correspond to the BC and AC speech signals, respectively.

Simultaneously recorded AC and BC speech signals of the five vowel sounds spoken by a female speaker and the autoregressive spectra and periodograms estimated from the AC signals of five consecutive 30 ms frames of each vowel sound are shown in Figs. 4 and 5, respectively. According to Figs. 4 and 5, the amplitude of BC speech spoken by the female speaker is also amplified for /i/ and /u/ with lower $F_1$ of the AC signal and reduced for /a/ with higher $F_1$ of the AC signal; this is similar to the case of male speech in Fig. 1. In both cases, the amplitude variation of BC speech is mainly determined by the $F_1$ value of the AC signal, whereas its $F_2$ value plays an additional role in amplification and reduction.

To generalize the findings, the $F_1$ and $F_2$ values obtained from AC signals with short-time magnitude ratios of BC and AC speeches spoken by eight speakers (four male MA1–MA4 and four female FE1–FE4) for close vowels /i/ and /u/ and open vowel /a/ are summarized in Table 1. Only the close and open vowels are chosen because they produce very obvious results for amplitude variation. Here, both $F_1$ and $F_2$ values are the mean values obtained from AC signals from a number of frames spanning the middle portion of every vowel sound estimated using the Praat [20] system. Similarly, the

**Table 1** $F_1$ and $F_2$ with short-time magnitude ratio of BC and AC signals of vowel sounds spoken by four male (MA1–MA4) and four female (FE1–FE4) speakers.

<table>
<thead>
<tr>
<th>Vowel</th>
<th>Speaker</th>
<th>$F_1$ (Hz)</th>
<th>$F_2$ (Hz)</th>
<th>$F_2/F_1$</th>
<th>BC/AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>/a/</td>
<td>MA1</td>
<td>680</td>
<td>1,113</td>
<td>1.64</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>MA2</td>
<td>647</td>
<td>1,054</td>
<td>1.63</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>MA3</td>
<td>634</td>
<td>1,088</td>
<td>1.72</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>MA4</td>
<td>713</td>
<td>1,375</td>
<td>1.93</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>FE1</td>
<td>815</td>
<td>1,258</td>
<td>1.54</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>FE2</td>
<td>933</td>
<td>1,310</td>
<td>1.40</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>FE3</td>
<td>999</td>
<td>1,407</td>
<td>1.41</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>FE4</td>
<td>747</td>
<td>1,196</td>
<td>1.60</td>
<td>0.77</td>
</tr>
<tr>
<td>/i/</td>
<td>MA1</td>
<td>322</td>
<td>2,346</td>
<td>7.28</td>
<td>2.32</td>
</tr>
<tr>
<td></td>
<td>MA2</td>
<td>255</td>
<td>2,367</td>
<td>9.28</td>
<td>2.56</td>
</tr>
<tr>
<td></td>
<td>MA3</td>
<td>265</td>
<td>2,169</td>
<td>8.18</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>MA4</td>
<td>293</td>
<td>2,410</td>
<td>8.22</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>FE1</td>
<td>314</td>
<td>2,773</td>
<td>8.83</td>
<td>1.96</td>
</tr>
<tr>
<td></td>
<td>FE2</td>
<td>301</td>
<td>2,723</td>
<td>9.04</td>
<td>2.50</td>
</tr>
<tr>
<td></td>
<td>FE3</td>
<td>371</td>
<td>2,848</td>
<td>7.67</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td>FE4</td>
<td>322</td>
<td>2,944</td>
<td>9.14</td>
<td>2.70</td>
</tr>
<tr>
<td>/u/</td>
<td>MA1</td>
<td>324</td>
<td>1,356</td>
<td>4.18</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td>MA2</td>
<td>336</td>
<td>1,515</td>
<td>4.51</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>MA3</td>
<td>305</td>
<td>1,604</td>
<td>5.26</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>MA4</td>
<td>309</td>
<td>1,393</td>
<td>4.51</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>FE1</td>
<td>432</td>
<td>1,486</td>
<td>3.43</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td>FE2</td>
<td>368</td>
<td>1,596</td>
<td>4.33</td>
<td>2.28</td>
</tr>
<tr>
<td></td>
<td>FE3</td>
<td>483</td>
<td>1,497</td>
<td>3.10</td>
<td>2.22</td>
</tr>
<tr>
<td></td>
<td>FE4</td>
<td>452</td>
<td>1,297</td>
<td>2.87</td>
<td>1.41</td>
</tr>
</tbody>
</table>
magnitude ratio BC/AC shown in Table 1 represents the mean of the magnitude ratios indicated in Fig. 3. For formant estimation, the Praat settings are configured as shown in Table 2.

As is obvious from Table 1, the maximum amplification of the BC speech amplitude is observed for the vowel /i/ with the lowest $F_1$ and a higher $F_3/F_1$ value, and the maximum reduction of BC amplitude is observed for the vowel /a/ with the highest $F_1$ and a lower $F_2/F_1$ value. However, since formant locations of voiced speech are related to physiology and vary among speakers, as do the bone and skin impedances, the extent of the observed results may differ among speakers. Therefore, in spite of the similarity of the amplitude behavior of a particular vowel sound, variability among the speakers is also evident in the BC/AC values in Table 1.

The results of an additional analysis of the effect of tongue movement from vowel to vowel are illustrated in Figs. 6, where Figs. 6(a) and 6(b) show the effect due to changes in the voice from /a/ to /i/ and /u/ to /i/, respectively. In both cases, the top, middle, and bottom plots show a fragment of the AC signal, a spectrogram of the AC fragment with formant tracks, and the corresponding fragment of the BC signal, respectively. In the case shown in Fig. 6(a), the tongue position moves from low to high, causing a transition of $F_1$ values from higher to lower (as seen in the spectrogram). This results in a reduction of the BC amplitude of /a/ and amplification of that of /i/.

On the other hand, in the case shown in Fig. 6(b), the tongue position moves from the back to the front, causing a transition of $F_2$ values from lower to higher (as seen in the spectrogram). This results in more amplification of the BC signal of the front vowel /i/ compared with that of the back vowel /u/.

### 3.2. Experiments on CV Sounds

In addition to the above distinct vowel sounds, the amplitude behavior of various CV sounds ending with vowel sounds /a/, /i/, /u/, /e/, and /o/ are studied. An AC speech segment, its spectrogram, and formant tracks together with the corresponding BC speech signals of ‘ga,’ ‘be,’ ‘no,’ ‘ni’ and ‘ru’ spoken by a male speaker are shown in Fig. 7.

As seen in Fig. 7, transitions of $F_1$ take place from consonant to vowel sounds. As in the case of distinct vowel sounds, the relative BC amplitudes of /a/, /e/, and /o/ with higher $F_1$ of AC signals are reduced and that of /i/ with lower $F_1$ is amplified with respect to the preceding consonant sounds. However, for the CV sound ‘ru,’ owing to lower $F_1$ in the preceding consonant /r/, the BC amplitude of /r/ is more amplified than that of /u/. Amplitude variations of various CV sounds spoken by a female speaker are shown in Fig. 8. With little variation due to physiological differences among the speakers, the nature of the amplitude variation observed in Fig. 8 is similar to that in Fig. 7.

### 3.3. Experiments on Natural Continuous Utterances

Compared with distinct vowel sounds, continuous speech exhibits complex characteristics owing to faster transitions of the vocal tract shape. We studied a number of simultaneously recorded utterances and observed similar trends of amplitude variation. Primarily, we attempt to observe the phenomenon in the long utterance, ‘isshukan bakari nyuyoku wo shuzaishita,’ spoken by a Japanese male speaker. The AC speech signal, its spectrogram with formant tracks, and the corresponding BC signal of the utterance are shown in Fig. 9. As discussed earlier in Sect. 3.1, every time the vocal tract shape is changed, transitions of formants take place. In particular, the variation of $F_1$ clearly displays sensitivity to vocal tract shape. The amplification and reduction of BC amplitude are apparent when the transitions of $F_1$ (to lower and to higher values, respectively) take place, as indicated by the arrows in Fig. 9(b). Furthermore, the short-time magnitude of the AC and BC speech in Fig. 9(d) quantitatively shows the relative amplification and reduction of BC amplitude compared with the AC counterpart. Here, the short-time magnitude is computed again as $\sum_{n=0}^{N-1} |s(n)|$ using frame length $N = 240$, where $s(n)$ indicates the underlying AC or BC speech signal. The signal, spectrogram, and short-time
magnitude of the same utterance (as in Fig. 9) spoken by a female speaker are shown in Fig. 10. Although the normalized magnitude does not represent the exact degree of amplification or reduction, a clear correspondence between the transition of $F_1$ of AC speech and the amplitude variation of BC speech is observed in Fig. 10. Typical variations are indicated with arrows in the figure.

4. AMPLITUDE BEHAVIOUR OF BC SPEECH IN FLAT MICROPHONE RESPONSE

According to Eq. (3), isolation of the microphone effect is necessary to study the exact amplitude behavior of BC speech. Unlike a normal air-conductive microphone that exhibits a nearly flat frequency response, the Temco HG-17 BCM is found to emphasize certain frequency components. The frequency response up to 4 kHz of the Temco HG-17 transducer is shown in Fig. 11. The data was collected personally from MacDonald et al. [21]. The response was obtained through a Bruel & Kjær artificial mastoid (Type 4930) using a train of eight 250 ms Gaussian noise bursts separated by 300 ms intervals as the stimulus. The frequency response of the transducer was estimated using
Fig. 9 (a) Long segment of AC speech spoken by male speaker MA4. (b) Spectrogram and formant tracks obtained from speech signal in (a). (c) Corresponding BC speech segment. (d) Short-time magnitude of AC (solid line) and BC speech (dotted line).

Fig. 10 (a) Long segment of AC speech spoken by female speaker FE1. (b) Spectrogram and formant tracks obtained from speech signal in (a). (c) Corresponding BC speech segment. (d) Short-time magnitude of AC (solid line) and BC speech (dotted line).
the MLSSA system [21]. An inverse filter was then created from the obtained response and applied to the BC speech signal. This resulted in a theoretically flat microphone response, and thus, the filtered BC speech became free from the microphone effect.

The primarily recorded BC signal of the vowel sounds in Fig. 4(b) and its filtered version are shown in Fig. 12 together with the corresponding magnitude ratio BC/AC obtained using the simultaneously recorded AC counterpart shown in Fig. 4(a). The magnitude ratio BC/AC is obtained similarly to in Fig. 3. According to Fig. 11, except in the very low frequency region (well before the first formant), no sharp peaks or dips are apparent in the frequency response of the Temco HG 17 transducer. Therefore, the isolation of the microphone effect does not affect the relative amplitude of BC speech except for an overall change in the amplitude (Fig. 12). This indicates that the amplitude behavior of BC speech described in Sect. 3 is primarily due to the impedance variations of the bone conduction pathways (i.e., skull bone and skin) which, in turn, depend on the spectral characteristics of AC speech.

5. CONCLUSIONS

In this paper, we presented the amplitude behavior of BC speech relative to AC speech. Since the vibrations transmitted from the oral cavity are impeded by the vocal tract wall and skull bone before being captured by a bone-conductive microphone, BC speech has modified formant locations compared with AC speech. We analyzed the BC signal of isolated vowel sounds, CV sounds, and long utterances spoken by Japanese male and female speakers. It was observed that the relative BC amplitude is very sensitive to the location of the first formant of AC speech. When the first formant was very low, the relative BC amplitude of the underlying segment was amplified and it was reduced for a higher first formant. Although the second formant played an additional role in amplification or reduction, its effect was somewhat less prominent. This variation in the relative BC amplitude may be mapped back to the formant adjustment of underlying BC speech, which will ultimately lead to more intelligible BC speech.

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REFERENCES

M. S. RAHMAN and T. SHIMAMURA: AMPLITUDE VARIATION OF BONE-CONDUCTED SPEECH


