# Phase Characteristics of Approximated Head-related Transfer Functions(HRTFs) Using IIR Filters on the Sound Localization

Kenichi KANAZAWA†, Hiroshi HASEGAWA†, Masao KASUGA†, Shuichi MATSUMOTO‡, Atsushi KOIKE‡, and Hideo YAMAMOTO†

†Department of Information Science, Faculty of Engineering, Utsunomiya University
7-1-2 Yoto, Utsunomiya 321-8585, Japan
Phone/Fax.: +81-28-689-6294, E-mail : kanaken@spela.is.utsunomiya-u.ac.jp
‡ KDD R&D Laboratory
2-1-15 Ohara, Kamifukuoka 356-8502, Japan

*Abstract*—**We have proposed a simple method based on IIR filters for realizing sound image localization. However the nonlinearity of phase characteristics of the IIR filters, which are used for sound image localization, cause decrease of the localization accuracy. In this paper we investigate the influence of phase characteristics on the sound localization. Head-related transfer functions (HRTFs) of a dummy-head are approximated by the IIR filter. We carried out sound image localization experiment with 2-loudspeaker reproduction using the approximated HRTFs. Then the errors which obtained from experiments were compared with the theoretical values which were estimated from the phase shifts of the IIR filters. As a result there was little influence of the nonlinear phase characteristics of the IIR filters in the localization on the horizontal plane.**

## I. Background And Purpose

Recent progress in digital signal processing techniques has made it possible to reproduce 3D sound fields based on high fidelity sound signals. The method for localizing sound images by using FIR filters that simulate head-related transfer functions (HRTFs) is regarded as one of the most important techniques. However it is difficult to control sound fields by such FIR filters, since the order of each FIR filter is high.

In previous papers[1]–[4] we proposed a simple method based on IIR filters for realizing sound image localization. Using this method the cost of multiplication operation in the filtering process can be reduced to possibly 1/15 to 1/30 of the case of the FIR filters. However the nonlinearity of phase characteristics of the IIR filters decrease of the localization accuracy. In this paper we investigate the influence of the nonlinear phase characteristics on the sound localization.

## II. Simulation of Sound Source with 2-loudspeaker Reproduction

Figure 1 shows a method to realize the sound localization in the case of 2-loudspeaker reproduction. $H_{\rm L}(\omega)$ and $H_{\rm R}(\omega)$ are the transfer functions from a sound source to the left and right entrances of the ear canals of the subject, respectively. $H_{\rm LL}(\omega)$, $H_{\rm RR}(\omega)$, $H_{\rm LR}(\omega)$, and $H_{\rm RL}(\omega)$ are the transfer functions from the loudspeakers to the left and right entrances of the ear canals of the subject, respectively. In order to simulate the source sound $S(\omega)$,

$$
\begin{aligned}
S_{\rm L}(\omega) &= \frac{H_{\rm RR}(\omega)H_{\rm L}(\omega)S(\omega) - H_{\rm RL}(\omega)H_{\rm R}(\omega)S(\omega)}{H_{\rm LL}(\omega)H_{\rm RR}(\omega) - H_{\rm LR}(\omega)H_{\rm RL}(\omega)}, \\
S_{\rm R}(\omega) &= \frac{H_{\rm LL}(\omega)H_{\rm R}(\omega)S(\omega) - H_{\rm LR}(\omega)H_{\rm L}(\omega)S(\omega)}{H_{\rm LL}(\omega)H_{\rm RR}(\omega) - H_{\rm LR}(\omega)H_{\rm RL}(\omega)}
\end{aligned}
\tag{1}
$$

are inputted into each loudspeaker.

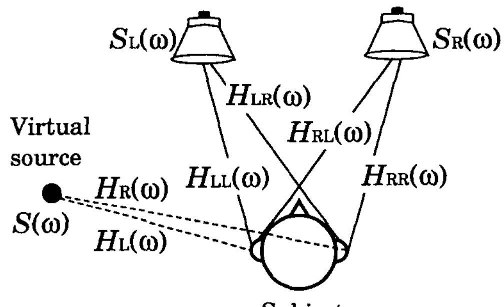


Fig. 1. Sound localization with 2-loudspeaker reproduction.

## III. Approximation of HRTF by using IIR Filter

### A. Design of IIR filter

We assume that the transfer function $H(z^{-1})$ of a IIR filter is

$$H(z^{-1}) = \prod_{i=1}^{n} a_{i0}\frac{1 + a_{i1}z^{-1} + a_{i2}z^{-2}}{1 + b_{i1}z^{-1} + b_{i2}z^{-2}} \tag{2}$$

where $a_{i0}$ is a normalization coefficient and $a_{i1}$, $a_{i2}$, $b_{i1}$, and $b_{i2}$ are filter coefficients[5][6].

The IIR filters are obtained from the $Z$-transforms of analog transfer functions. Then the amplitude characteristics of HRTFs of a dummy-head are approximated by the IIR filters. In this approximation, the measured HRTFs that are Web-published by MIT Media Lab. are used[7]. Each head-related impulse response (HRIR : 512 samples, 44.1 kHz), which is referred to each HRTF is measured at the left ear canal entrance of a dummy-head (KEMAR, Knowles Electronics model DB-4004) in an anechoic chamber. The HRTFs of 24 different directions on the horizontal plane from −180 degrees to 180 degrees (the facing direction of the dummy-head as 0 degrees) are simplified with 31-point moving average in the frequency range 20 Hz to 20 kHz. The simplified HRTFs are approximated by IIR filters as follows:

( i ) the HRTFs are approximated by fourth to seventh-order IIR filters (the difference between the amplitude characteristic of the designed IIR filter and that of the HRTF in each direction is within ±5 dB in the frequency range 20 Hz to 10 kHz),

( ii ) the HRTFs are approximated by third-order IIR filters.

Figure 2 shows examples of the approximated HRTFs.

*B. Interaural time difference*

Interaural time differences (ITDs) must be considered since the IIR filters give only amplitude characteristics.

A sound wave from a distant source that strikes a spherical head of radius $r$ from a direction specified by the azimuth angle $\theta$ is considered. The (ITD) $\tau$ is

$$\tau = \frac{r(\theta + \sin\theta)}{c}, \quad (3)$$

where $c$ is the speed of sound.

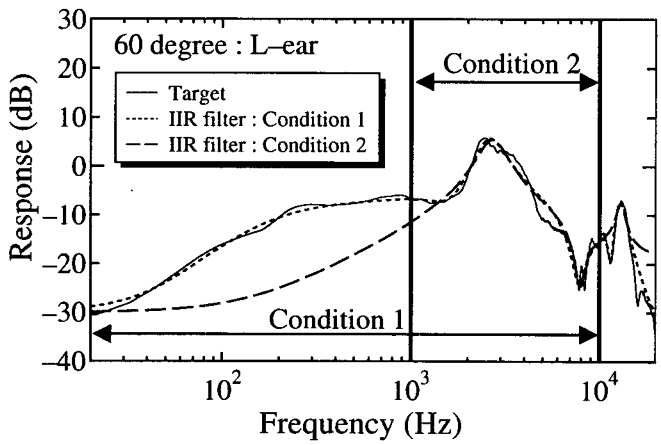


Fig. 2. Example of the approximated HRTFs by the IIR filter. The target is the HRTF at the entrance of the left ear canal from a loudspeaker located 1.4 m away from the center of the dummy-head and −120 ° azimuth.

## IV. Sound Localization Experiment

*A. Sound stimulus*

The sound stimuli for the experiment are obtained from inputting the source signal into the following filters:

(A) FIR filters that simulated the measured HRTFs,

(B) fourth to seventh-order IIR filters in Sect. 2 ( i ),

(C) third-order IIR filters in Sect. 2 ( ii ).

The output signals from (B) and (C) are given the ITDs.

*B. Experiment 1*

Sound localization tests on the horizontal plane were carried out in a soundproof chamber (D-30, 4278 (W) × 3673 (D) × 2510 (H)). Three subjects in the 20 generation with the normal hearing ability were tested in this experiment. The sound stimuli were presented via 2-loudspeaker placed symmetrically in front of a subject (±10 degrees azimuth on the horizontal plane). Distance between the subject and each loudspeaker was 2 m. The head of the subject was fixed by means of a chin support installed in the front of the subject.

For cancellation of the spatial responses in the chamber and the frequency characteristics of the loudspeakers, the impulse responses at the entrances of the two auditory canals of each subject were measured by using a time-stretched pulse emitted from each loudspeaker[8][9]. After the deconvolution of these responses and the cross-talk cancellation, the sounds from 24 different directions on the horizontal plane were simulated. A voice of a woman announcer for 3 seconds was used as the source signal of the sound stimuli. Each sound stimulus was presented 5 times in each direction. Then the subjects replied about the perceived direction of the sound image corresponding to the sound stimulus.

*C. Result1*

Figures 3 (a), (b), and (c) show the experimental results of the perceived directions of the sound images on the horizontal plane using approximated HRTFs of the filters (A), (B), and (C), respectively. The area of each circle is proportional to the number of the responses of the subjects within a range of 15 degrees. The thin lines show that the simulated directions of the sound images correspond to the perceived directions, and the dotted lines show that the simulated sound images symmetrically localized on the interaural axis. The thick lines and the error bars show the mean values and the standard deviations of the perceived directions, respectively. In the case of the FIR filters (A) (Fig. 3(a)), the simulated directions of the sound images in the front agreed well with the perceived directions. A few numbers of the front-rear judgment errors were caused in the simulated direction of the front (−60, −45, and 30 to 75 degrees azimuth). It is considered that these errors were caused by not using their personal HRTFs but using the HRTFs of a dummy-head.

In the result of the IIR filters (B) (Fig. 3(b)), though the front-rear judgment error increased a little in the simulated direction of the rear (−165 to −105 and 105 to 180 degrees azimuth), it is almost similar to the result of Fig. 3(a).

In the result of the IIR filters (C) (Fig. 3(c)), the front-rear judgment error increased not only in the simulated directions of the rear sound images(−165 to −105 and 105 to 180 degrees azimuth) but also in the directions of the front (−75 to −15 and 15 to 75 degrees azimuth). However most sound images are localized in the simulated directions.

*D. Experiment 2*

In this experiment sound localization tests were carried out by using the sound stimuli of a pink noise and 7 kinds of 1 octave band noises (center frequencies 125, 250, 500, 1000, 2000, 4000, and 8000 Hz), and the errors of the directional localization were measured. Five subjects were tested in this experiment. The sound stimuli were reproduced via 2-loudspeaker placed symmetrically in front of a subject (±30 degrees). Distance between the subject and each loudspeaker was 1.55 m. The head of the subject was fixed by means of a head support installed in the rear of the subject with a rubber band. Other experimental conditions were the same as Experiment 1.

The sounds were simulated in 5 directions of the every 15 degrees from the front to the right side of a subject on the horizontal plane.

*E. Result2*

We estimated the theoretical values of directional errors from the phase shifts of the IIR filters (B) and (C). The theoretical values were compared with the errors obtained from Experiment 2. Figures 4(a), (b), (c), and (d) show the theoretical values and the errors at directions 15, 30, 45, and 60 degrees, respectively. The gray solid and dotted lines show the theoretical values of the filters (B) and (C), respectively. The symbols □ and ○ show the errors in the case of the filters (B) and (C), respectively. Positive value of the direction and phase differences show that the sound localization shifts rightward.

As a result the errors almost corresponded with the theoretical values. The largest error was about 5 degrees difference for the pink noise and was about 10 degrees difference for the band noises. The largest theoretical error of the directions which were not tested in Experiment 2 (larger than 60 degrees) was about 15 degrees difference. From the above fact it is noted that there is little influence of the nonlinear phase characteristics of the IIR filter in the localization on the horizontal plane.

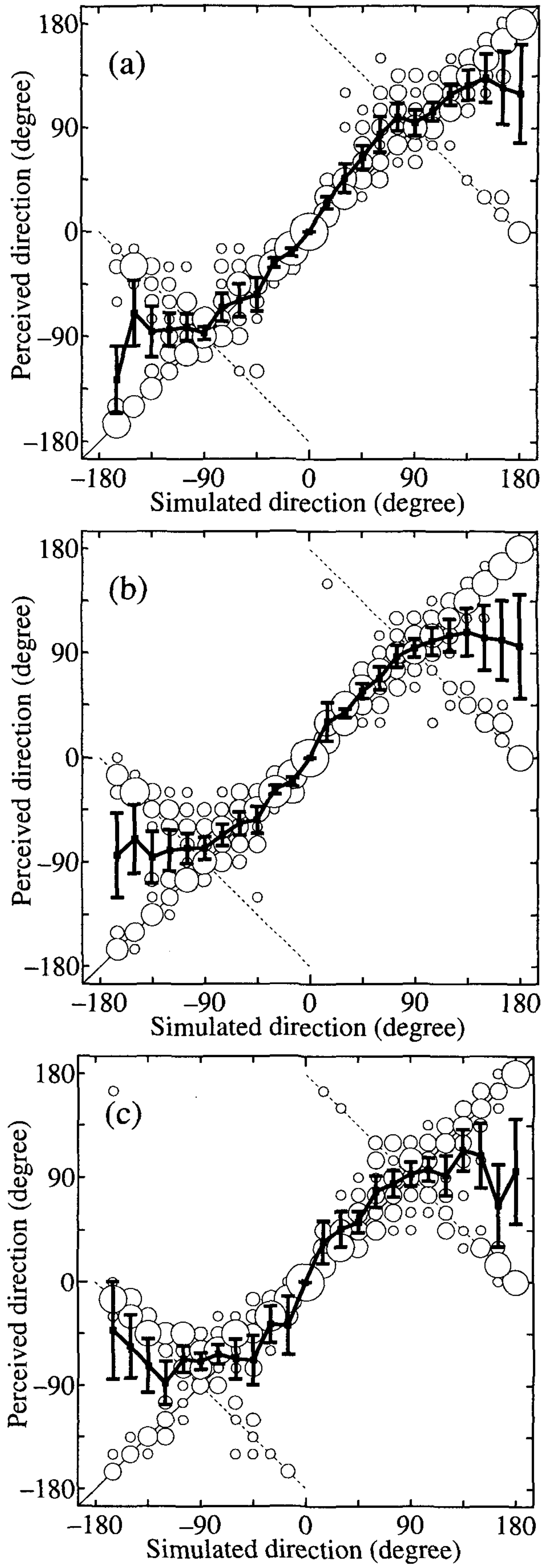


Fig. 3. Sound localization on the horizontal plane. The results of the filters (A), (B), and (C), respectively.

## V. Discussion

HRTFs of a dummy-head were approximated by our simple IIR filters. The sound localization tests on the direction were carried out with 2-loudspeaker reproduction. The experimental results of the IIR filters almost agreed with the results of the FIR filters.

We estimated the theoretical values of directional errors from the phase shifts of the IIR filters. These values were compared with the errors obtained from the sound localization experiments. As a result the errors almost corresponded with the theoretical values. The largest error contained about 10 degrees difference for the band noises. This result shows that the approximation technique of HRTFs based on our IIR filters is effective for the sound localization on the horizontal plane. This means that it is possible to create high fidelity sound fields with transaural reproduction more simply.

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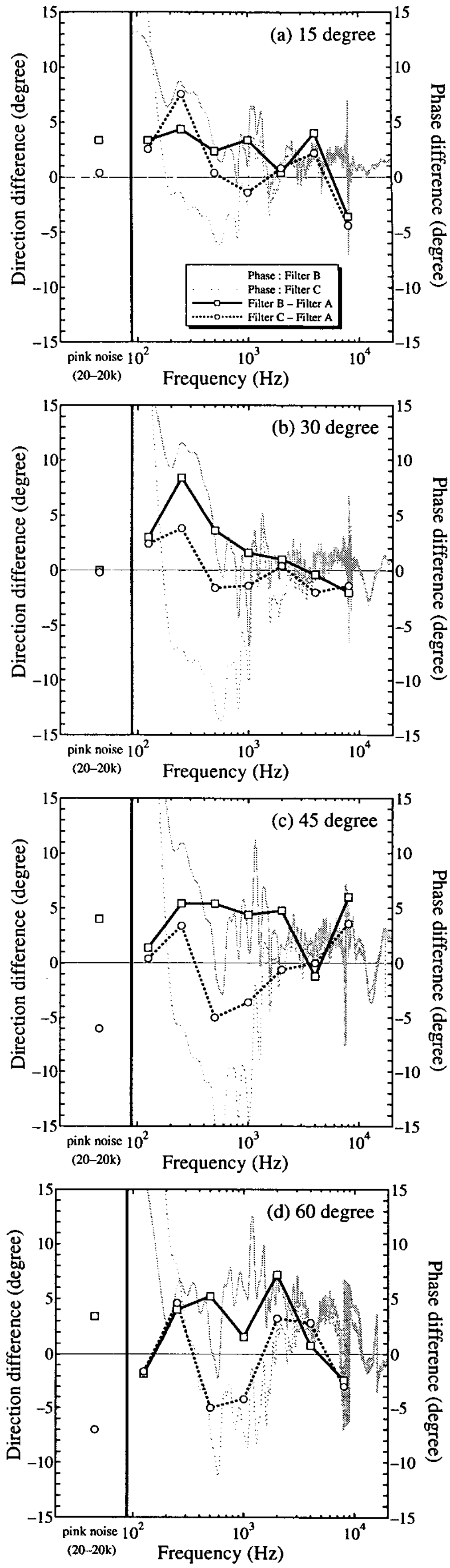


Fig. 4. theoretical values estimated from the phase shifts of the IIR filters and errors obtained from experiments.