

# Binaural Directivity Pattern Measurements of the KEMAR Head Model with Two Twin Hearing Aid Microphones

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## Abstract

Two twin microphones may produce particular patterns of binaural directivity by time delays between the twin microphones. The boundary element method (BEM) was used for the simulation of the sound pressure field around the KEMAR head model in order to quantify the acoustic head effect. The sound pressure onto the microphone was calculated by the BEM to an incident sound pressure. Then a planar directivity pattern was formed by four sound pressure signals from four microphones. The optimal binaural directivity pattern may be achieved by adjusting time delays at each frequency while maintaining the forward beam pattern is relatively bigger than the backward beam pattern. The simulation results were verified by the experimental measurement.

**Keywords:** Hearing Aid, Planar Binaural Directivity Pattern, Microphone Array, BEM, KEMAR Head Model.

## 1. Introduction

One of the advanced features of the digital hearing aid (HA) chip is its parameter adjusting function[1]. One particular feature we consider in this paper is the directivity of the digital HA. More microphones than a single microphone are used for making directional HA[2]. The directional HA may have the relatively increased sensitivity to the sound coming from a particular direction. This geometrical feature effectively improves the noise reduction in the presence of the environmental noise. Each of the right and the left ears may be fixed by an ITE(In The Ear) hearing aid with a pair of microphones. These two twin microphones can produce particular patterns of directivity by time delays between the twin microphones[3].

Audiologists recommend the binaural fitting of HAs. That is to fit each ITE HA into the right and left ears simultaneously. The one sided fitting is called as monaural fitting which is

ineffective in directivity (monaural directivity). Each of the right and the left ears may be fixed by an ITE HA with a pair of microphones. If two microphones are built in an ITE HA, the binaural fitting of HAs means two twin microphones; total 4 microphones. These two twin microphones can produce particular patterns of directivity (binaural directivity) by time delays between the twin microphones[4]. Two microphones in an ITE HA can be synchronized, that is, both microphones are connected to a digital amplifier with two input channels. Those two channels of input signals may be summed with time delays between the two signals. However the other two microphones in the left ear are not synchronized with those two microphones in the right ear. When microphone arrays are placed near to the head, the performance of arrays is modified because of the acoustic head effect. Then, how can binaural directivity be evaluated systematically? Our previous paper showed the solution by a numerical simulation, based on the boundary element method (BEM)[4]. We calculated sound pressures onto the ear canal of a dummy head model for an incident pressure from any spherical direction using the BEM. We, in this paper, consider an

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experimental verification of the numerical results of the binaural directivity.

## II. Boundary Element Mesh Generation

The BEM was used for the simulation of the sound pressure field around a head model. The BEM numerical solution for the directional HA is to calculate the sound pressure on the ear of the head model. The sound pressure onto the microphone fitted in the ear was calculated by the BEM to an incident sound pressure. Then a planar binaural directivity pattern was formed by four sound pressures from four microphones. The time delay between twin microphones was changed to produce the most optimal directivity pattern. The details of the BEM are well documented in the previous paper[4].

The KEMAR (Knowles Electronics Manikin for Acoustic Research), a dummy head model, was three dimensionally scanned by a laser scanner[5]. The scanned points data of the three dimensional coordinates were then used to be meshed for boundary surface element grids[6]. Each boundary element has 4 corner nodes and 4 mid side nodes. It is a common practice to have the size of the largest surface element be at least less than  $\lambda/3$  ( $\lambda$ =wavelength), so that the numerical approximation might be converged[7]. In this paper, the upper frequency of the acoustic radiation is less than 4 kHz, so that  $\lambda/3$  is about 0.283 m. Figure 1 shows the surface element meshes of the KEMAR model. The angle of the directivity pattern starts from the front in anti clockwise direction.

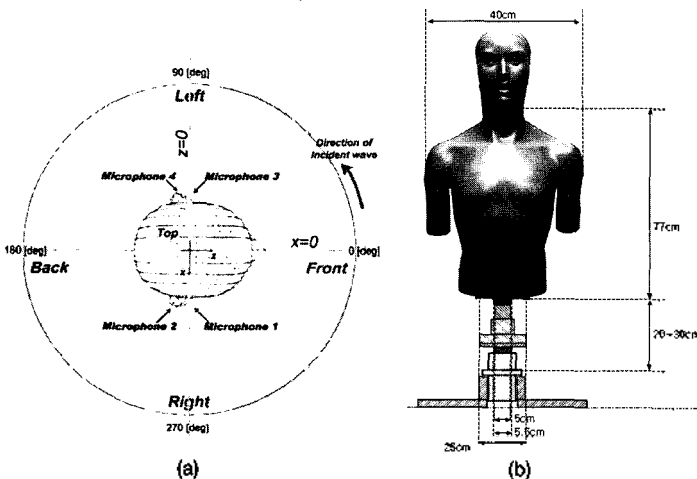


Fig. 1. (a) Polar coordinates for directivity pattern calculation, Microphone 1 and 3 are reference, Microphone 1 and 2 are positioned onto the ITE HA of the right ear and are separated each other in 10mm in the frontal direction while microphone 3 and 4 are positioned in the left ear in the same way as the right ear, (b) The KEMAR model is rotated by a stepping motor.

## III. Time Delay Method

Figure 2 shows time delay ( $\Delta t$ ) circuits between the front and the rear microphones (Mic. 1 and Mic. 2 or Mic. 3 and Mic. 4 respectively). In figure 2, a signal from the front reference microphone is summed with a time delayed signal from the rear microphone. The amount of the time delay may be expressed in phase angle,  $2\pi f \cdot \Delta t$ .

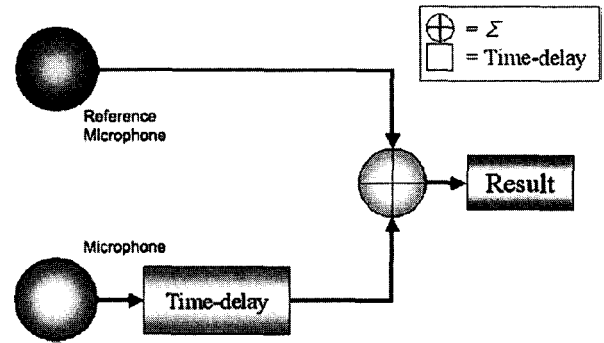


Fig. 2. Time delay ( $\Delta t$ ) circuits between front and rear microphones (Mic. 1 and Mic. 2 or Mic. 3 and Mic. 4 respectively), Reference microphone (0 time delay) = front microphone (Mic. 1 and Mic. 3), 'd' =the distance between twin (the front and the rear) microphones (Mic 1 and Mic 2, Mic 3 and Mic 4). 'd' =10mm separation.

In figure 2, the strength of the resulted sound pressure from the two twin microphones is calculated by equation (1);

$$Y_{Bi} = |Y_{right}(t) + Y_{left}(t)| \quad (1)$$

$$= |A_2 \cdot \cos(2\pi f(t - \Delta t - T_{12})) - A_1 \cdot \cos(2\pi f(t - T_{11})) + |A_4 \cdot \cos(2\pi f(t - \Delta t - T_{14})) - A_3 \cdot \cos(2\pi f(t - T_{13}))|$$

where  $A_i$  is the amplitude of the  $i$ th microphone and  $T_{ij}$  is the time (phase) difference between the  $i$ th and the  $j$ th microphones which is measured as shown in figure 3.  $T_{11} = 0$ .

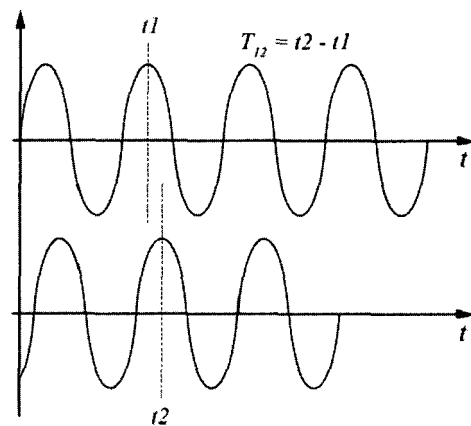


Fig. 3. Time (Phase) difference between two signals.

## IV. Experimental Apparatus

The whole procedure of the electro acoustic experiment was automated by a LabView program in an anechoic room (Fig. 4).

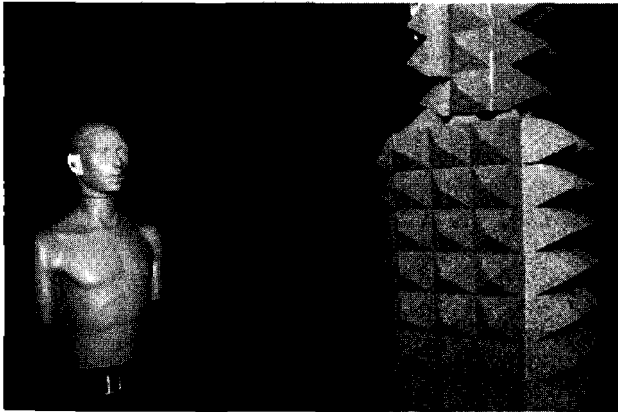


Fig. 4. KEMAR model in an anechoic room with a speaker covered with sound absorbing materials (polyurethane foam). The KEMAR model and the speaker were separated by 1m.

Figure 5 and figure 6 show the frontal panels of the LabView programs which control and communicate through NI (National Instrument) boards. The experimental data were acquisitioned through NI boards (NI PCI 6251 and NI PCI 6733, National Instrumentation Co., USA). The testing sound signal was generated by a 15W speaker connected with a HP 33120A function generator controlled by the LabView program (Fig. 5) through a RS232 serial port. NI PCI 6251 (250k samples/sec for each channel) acquisitioned output signals of 4 HA microphones (EK3133, Knowles Co. Malaysia). The four HA microphones were 1.4V DC power supplied for internal amplification. The KEMAR model was precisely rotated by a stepping motor in which a motor driver and a controller were controlled by the LabView program through another RS232 serial port (Fig. 5).  $T_{ij}$ , the time(phase) difference between the  $i$ th and the  $j$ th microphone in equation 1 was measured by a FFT technique in the LabView program (Fig. 5). Then, the time delayed signal  $Y_{right}(t)$  and  $Y_{left}(t)$  were generated through a stereo headphone (HD250 Linear II, Sennheiser Co, Germany) driven by NI PCI 6733 (1M samples/sec for each channel) which was controlled by the LabView program (Fig. 6). The binaural directivity pattern was formed and plotted as the response of the stereo headphone listener. Figure 7 shows the KEMAR model with two ITE HAs in the right and the left ears. Each ITE HA has two HA microphones separated by 10mm. Figure 8 shows ear models and the ITE HA shells for the KEMAR (a) and a PCB circuitry of the ITE HA for signal processing (b).

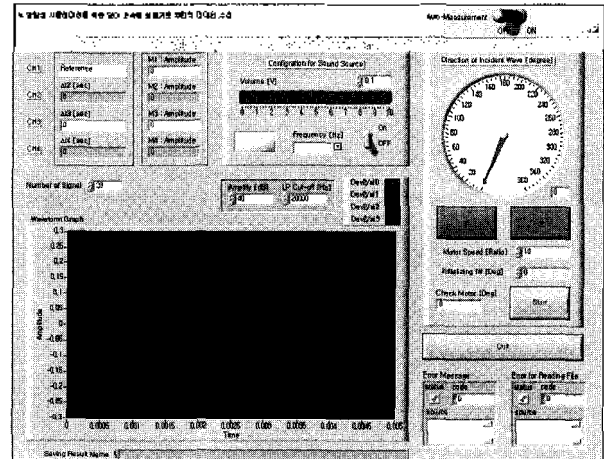


Fig. 5. The frontal panel of the LabView program which controls and communicates through NI PCI 6251 board. The experimental data were acquisitioned through the NI board. The LabView program was developed by the author.

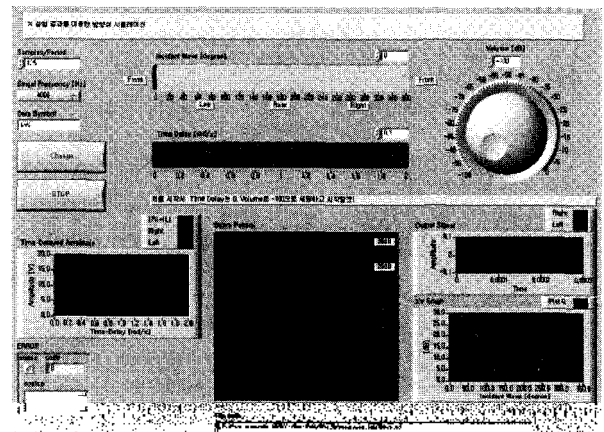
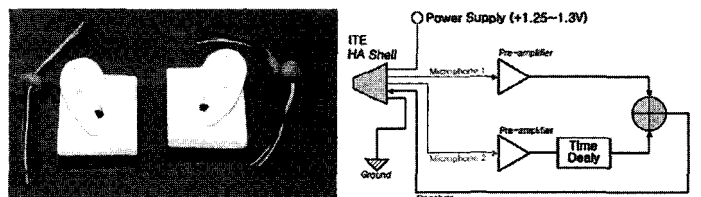


Fig. 6. The frontal panel of the LabView program which controls and communicate through NI PCI 6733 board. The binaural directivity pattern was formed and plotted as the response of the stereo headphone listener. The LabView program was developed by the author.



(a) External view, (b) Internal view.

Fig. 7. The KEMAR model with two ITE HAs in the right and the left ears. Each ITE HA has two HA microphones separated by 10mm.



(a) Ear models and ITE HA shells, (b) A PCB circuitry of ITE HA for signal processing.

Fig. 8. ITE HA shells for the KEMAR.

## V. Results

The complex values of the sound pressure onto four microphones on the inlet of the right and the left ear canals were calculated both by SVS (BEM codes) and by measurement.

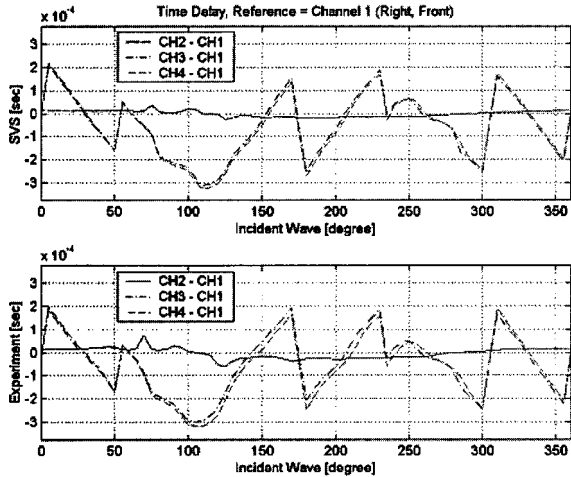


Fig. 9. Time differences,  $T_{ij}$ , between the  $i$ th channel (Mic.1 reference) and other three  $j$ th channels at 4 kHz.

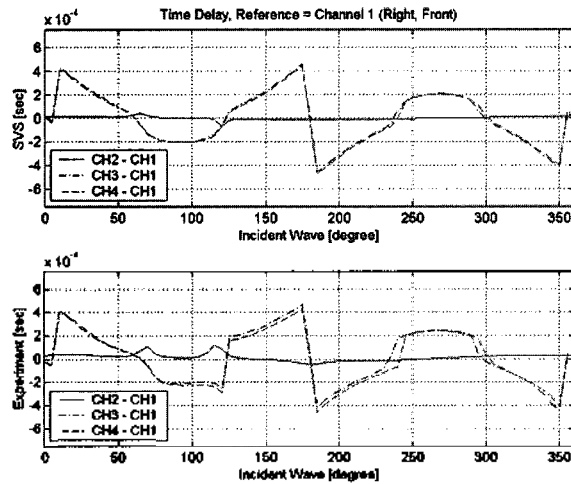


Fig. 10. Time differences,  $T_{ij}$ , between the  $i$ th channel (Mic.1 reference) and other three  $j$ th channels at 2 kHz.

Figure 9 shows time differences,  $T_{ij}$ , between the first  $i$ th channel (Mic.1 reference) and other three  $j$ th channels at 4 kHz. Angles of incident sound waves are indicated in Fig. 1(a). Figure 10 shows the time differences at 2 kHz. Both figures well verify the accuracy of the BEM programming. The time difference information of Fig. 9 and Fig. 10 indicates the phase difference information between four microphones. Both the phase as well as the amplitude of the sound pressure are used for the calculation of the strength of the resulted sound pressure in a directional HA as shown in equation (1). The directional HA can change the time delay ( $\Delta t$ ) between two microphones as shown in Fig. 2.

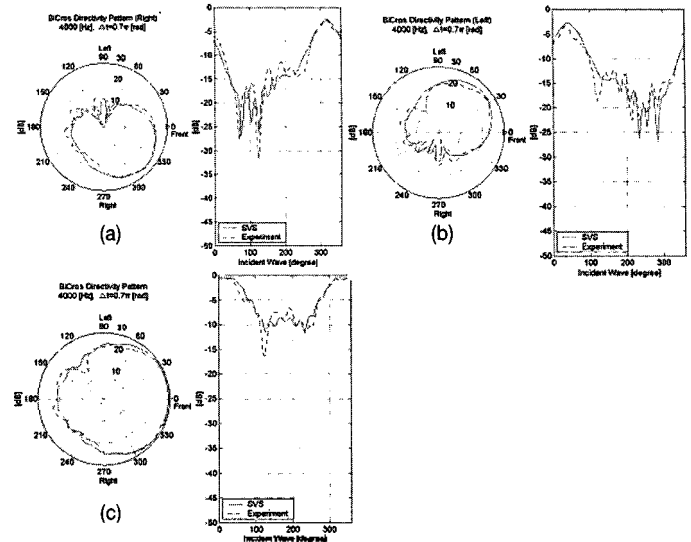


Fig. 11. The directivity and strength of the summed signal from the two microphones, (a) Mic. 1 & Mic 2,  $|Y_{right}(t)|$ , (b) Mic. 3 & Mic 4,  $|Y_{left}(t)|$ , (c)  $|Y_{left}(t)| + |Y_{right}(t)|$  at the frequency of 4 kHz and for the phase delay of  $2\pi f \cdot \Delta t = 0.7\pi$ .

Figure 11 shows the directivity pattern and the strength sensitivity of the summed signal for all combinations of the two microphones at 4 kHz. The phase delay ( $2\pi f \cdot \Delta t$ ) was fixed to be  $0.7\pi$ . Fig. 11 (a) is  $|Y_{right}(t)|$  from Mic. 1 & Mic 2 while Fig. 11 (b) is  $|Y_{left}(t)|$  from Mic. 3 & Mic 4. Fig. 11 (c) is  $|Y_{left}(t)| + |Y_{right}(t)|$  from (a) and (b). The same plots at the frequency of 2 kHz are given in Figure 12. From the figures it is clear that we can have better directivity patterns as frequency gets higher. However the sensitivity strength should be also considered.

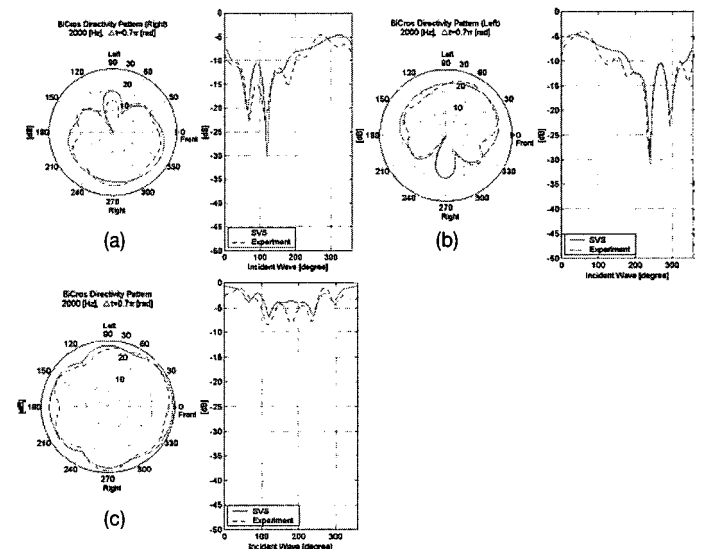
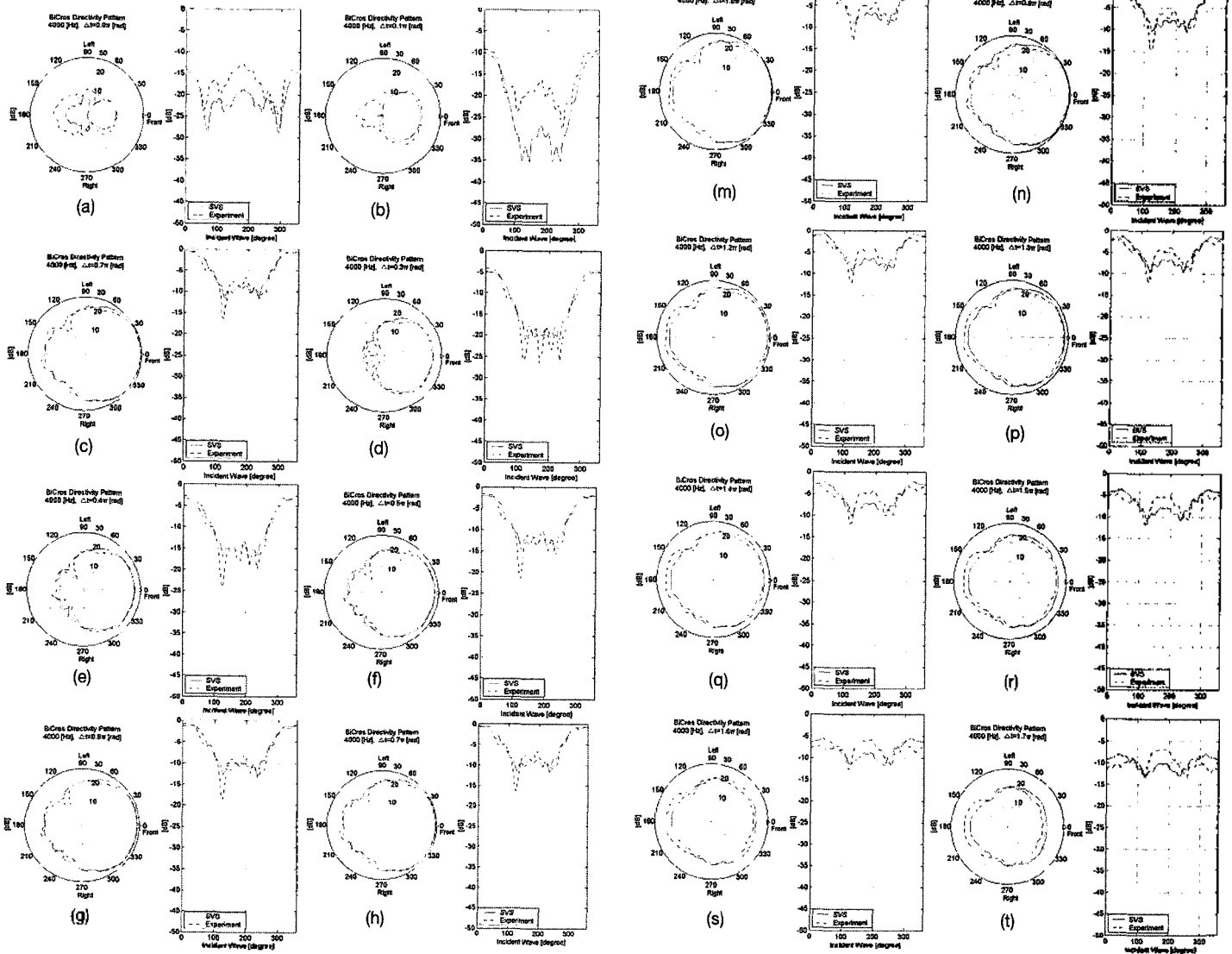


Fig. 12. The directivity and strength of the summed signal from the two microphones, (a) Mic. 1 & Mic 2,  $|Y_{right}(t)|$ , (b) Mic. 3 & Mic 4,  $|Y_{left}(t)|$ , (c)  $|Y_{left}(t)| + |Y_{right}(t)|$  at the frequency of 2 kHz and for the phase delay of  $2\pi f \cdot \Delta t = 0.7$ .

Figure 13 shows the directivity patterns and the strength sensitivities of the summed signal, at the frequency of 4 kHz, from the four microphones, namely,  $|Y_{left}(t) + Y_{right}(t)|$  as the phase delay ( $2\pi f \cdot \Delta t$ ) increases from 0 to  $2.0\pi$  by  $0.1\pi$ . It is clear that, from Fig. 13, the time delay ( $\Delta t$ ) influences greatly both the directivity patterns as well as the strength sensitivities and thus can be taken as a potential control parameter in order to get an optimal directivity pattern. Even though the directivity pattern becomes narrow, if the strength sensitivity becomes low, the resulted S/N ratio becomes worse than those of a single microphone HA. It is observed that, as the phase delay  $2\pi f \cdot \Delta t$  is close to  $0.7\pi$ , both the directivity pattern and the signal strength sensitivity look optimal (Fig. 11 (c) for 4kHz and Fig. 12(c) for 2 kHz). It should be noticed that this result included the acoustic shadow effect of the head.



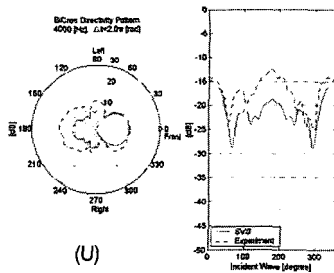


Fig. 13. The directivity and strength of the summed signal, at the frequency of 4 kHz, from the four microphones, namely,  $|Y_{left}(t)| + |Y_{right}(t)|$  at different phases ( $2\pi f \cdot \Delta t$ ). (a)  $\Delta t = 0.0\pi$ , (b)  $\Delta t = 0.1\pi$ , (c)  $\Delta t = 0.2\pi$ , (d)  $\Delta t = 0.3\pi$ , (e)  $\Delta t = 0.3\pi$ , (f)  $\Delta t = 0.4\pi$ , (g)  $\Delta t = 0.5\pi$ , (h)  $\Delta t = 0.6\pi$ , (i)  $\Delta t = 0.7\pi$ , (j)  $\Delta t = 0.8\pi$ , (k)  $\Delta t = 0.9\pi$ , (l)  $\Delta t = 1.0\pi$ , (m)  $\Delta t = 1.1\pi$ , (n)  $\Delta t = 1.2\pi$ , (o)  $\Delta t = 1.3\pi$ , (p)  $\Delta t = 1.4\pi$ , (q)  $\Delta t = 1.5\pi$ , (r)  $\Delta t = 1.6\pi$ , (s)  $\Delta t = 1.7\pi$ , (t)  $\Delta t = 1.8\pi$ , (u)  $\Delta t = 1.9\pi$ .

## VI. Conclusions

The present paper dealt firstly the simulated sound pressures onto two twin microphones fixed in the right and the left ears of the KEMAR head model by the BEM. Then the direction of the incident sound pressure was changed from 0 degree to 360 degree around the head model. The complex values of the sound pressures onto the 4 microphones calculated by the BEM represented the input sound pressures of the 4 channels of the binaural HAs. Secondly, the calculated complex sound pressure values were systematically modified in order to represent the time delay effects of the binaural HAs. Thus a binaural directivity was achieved systematically. Then, planar binaural directivity patterns were derived by varying time delays between twin microphones. Two factors were considered for the optimal directivity pattern. One is the planar binaural directivity pattern. The other is the receiving sensitivity of the binaural HA. The simulated results were verified by comparing with experimental results.

The optimal directivity pattern may be achieved by adjusting time delays at each frequency while maintaining the forward beam pattern is relatively bigger than the backward beam pattern. From the results the time delay ( $2\pi f \cdot \Delta t$ ) between two microphones was optimally chosen as to be  $0.7\pi$ [Rad] at 4 kHz when the two microphones were separated by 10mm. This result can be directly applied to commercial directional HAs because most directional HAs have their twin microphones placed 10mm away each other. It should be noticed that this result included the acoustic shadow effect of the head.

The present paper considers the experimental verification of

our previous numerical analysis on sound pressures onto the two twin microphones fixed in the right and the left ears of the KEMAR head model. The complex sound pressures onto the 4 microphones, which represent the input sound pressures to the 4 channels of the binaural HA, were calculated for incident sound waves with the angle from 0 to 360 degree, using the BEM. It was shown that the planar directivity patterns are characteristically similar between the measurement and the numerical prediction. We observed that, when the two microphones were separated by 10mm, the optimal directivity pattern at 4 kHz was achieved for the time delay satisfying that  $2\pi f \cdot \Delta t = 0.7\pi$ . It is expected that this study will play an important role in optimizing commercial directional HAs.

## Acknowledgment

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