

Sound source localization using scattered acoustic pressure on the surface of rigid sphere and its performance

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ABSTRACT

Sound visualization techniques, which visualize the useful information about sound source such as direction of incident wave from measured signal by directional microphone array, can be applied to visual aids for a hearing impaired person. Beamforming method is a novel way to visualize the sound and is advantageous in rapid realization using fewer microphones.

Visual aids are applied as a shape of helmet or glasses, should consider the effect of scattering by visual aids or user's head. In this paper, we modeled the scatterer as a rigid sphere and then used the beamforming method to estimate the direction of incident wave considering scattered acoustic pressure on the surface of rigid sphere as a bearing function. In addition, the resolution analysis was performed and was compared with the conventional beamforming method.

1. INTRODUCTION

Sound visualization technique is a method which expresses the invisible acoustical information such as the spatial distribution of acoustic pressure, radiation pattern, etc. to the visual information using directional microphone array. Sound visualization technique is a useful way when we want to estimate the location of the sound source or direction of incident wave. Acoustic holography^[1-3] and beamforming method^[4-6] are two typical ways to visualize those information. Such visualization method can be applied to some kind of visual aids for the hearing-impaired. The visual aids can help the hearing-impaired by providing visual information about sound or noise source, replacing their hearing (figure 1). Such devices demand the relatively free shape of microphone array and rapid calculation speed for the wearer's prompt action with the situation. In this case, sound visualization using beamforming method is a novel way to realize such devices because it needs only a few numbers of sensors and relatively less calculation time. The visual aids can be applied as a shape of helmet or glasses and the scattered sound by visual aids or wearer's head is also included in measured data as well as the incident sound like figure 2. This scattered sound may affect to the performance of the result of the sound visualization positively or negatively and should consider the effect of scattering. The objective of this paper is to see the effect of scattering to the performance of beamforming method. To do this, we first model the wearer's head or visual aids as a rigid sphere and then use the beamforming method to estimate the direction of incident wave considering scattered acoustic pressure on the surface of rigid sphere as a bearing function. In addition, the resolution analysis was

performed and was compared with the conventional beamforming method.

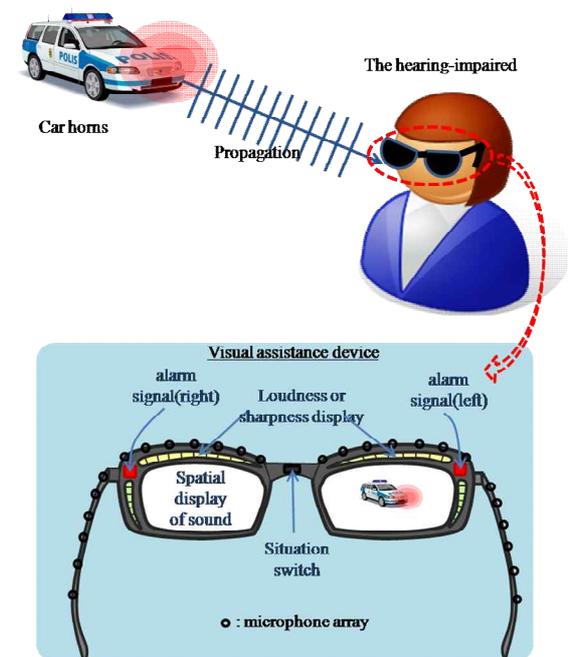


Figure 1. Concept of the visual assistance device for the hearing-impaired

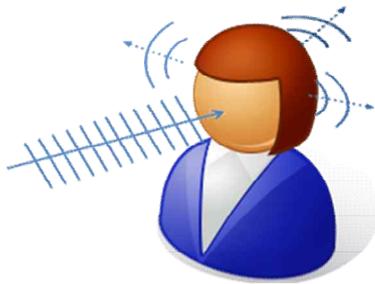


Figure 2. Scattering by the user's head

2. BEAMFORMER WITH SCATTERING EFFECT

2.1 Scattering of a plane wave from rigid sphere [7]

When a plane wave is propagated from (θ_s, ϕ_s) direction, the total sound field around the surface of a rigid sphere is composed of two components: one is the incident wave component and another is the scattered sound field. The total field is mathematically expressed as

$$P_{tot}(r, \theta, \phi; f) = P_{in}(r, \theta, \phi; f) + P_{sc}(r, \theta, \phi; f), \quad (1)$$

where $P_{tot}(r, \theta, \phi; f)$ stands for the total sound field at (r, θ, ϕ) , $P_{in}(r, \theta, \phi; f)$ is the sound field generated by incident wave component and $P_{sc}(r, \theta, \phi; f)$ the scattered sound field. The sound field generated by incident wave with unity magnitude $P_{in}(r, \theta, \phi; f)$ is defined as equation (2).

$$P_{in}(r, \theta, \phi; f) = \sum_{n=0}^{\infty} \sum_{m=-n}^n 4\pi i^n Y_n^m(\theta_s, \phi_s) j_n^{(1)}(kr) Y_n^m(\theta, \phi). \quad (2)$$

In addition, the scattered sound field by a rigid sphere $P_{sc}(r, \theta, \phi; f)$ is expressed as

$$P_{sc}(r, \theta, \phi; f) = \sum_{n=0}^{\infty} \sum_{m=-n}^n 4\pi i^n Y_n^m(\theta_s, \phi_s) \times \frac{j_n^{(1)}(ka)' h_n^{(1)}(kr)}{h_n^{(1)}(ka)'} Y_n^m(\theta, \phi). \quad (3)$$

In the equation (2) and (3), the function $Y_n^m(\theta_s, \phi_s)$ is defined as equation (4) and represents the spherical harmonics of

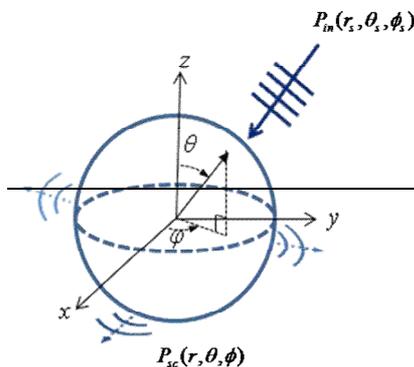


Figure 3. Plane wave ($P_{in}(r, \theta, \phi; f)$) propagation from (r_s, θ_s, ϕ_s) direction and scattered sound field ($P_{sc}(r, \theta, \phi; f)$) by a rigid sphere with radius a

order n and degree m . In addition, the function $j_n^{(1)}(kr)$ means the spherical Bessel functions of order n , $h_n^{(1)}(kr)$ is the spherical Hankel function of the first kind.

$$Y_n^m(\theta, \phi) \triangleq \sqrt{\frac{(2n+1)(n-m)!}{4\pi(n+m)!}} P_n^m(\cos\theta) e^{im\phi}. \quad (4)$$

The total sound field can be obtained from the equation (2) and equation (3), and is expressed as

$$P_{tot}(r, \theta, \phi; f) = \sum_{n=0}^{\infty} \sum_{m=-n}^n 4\pi i^n Y_n^m(\theta_s, \phi_s) \times \left(j_n^{(1)}(ka) - \frac{j_n^{(1)}(ka)'}{h_n^{(1)}(ka)'} h_n^{(1)}(kr) \right) Y_n^m(\theta, \phi). \quad (5)$$

2.2 Principles of conventional beamformer

The principle of conventional beamformer in the frequency domain is displayed in Figure 4. Conventional frequency domain beamformer obtain the beam power by properly compensating the phase difference caused by the difference of sound propagation path between sound source and each microphone. The beam power is defined as

$$BP = |\mathbf{P}^H \mathbf{W}|^2 = |\langle \mathbf{P}, \mathbf{W} \rangle|^2, \quad (6)$$

where $\mathbf{P} = [P_1 \ P_2 \ \dots \ P_M]^T$ represent the $M \times 1$ complex amplitude of the measured acoustic pressure vector and $\mathbf{W} = [W_1 \ W_2 \ \dots \ W_M]^T$ is the $M \times 1$ complex amplitude of the scanning vector. At this moment, the scanning vector \mathbf{W} includes the sound propagation model from the sound source and compensates the phase difference caused by the difference of sound propagation path.

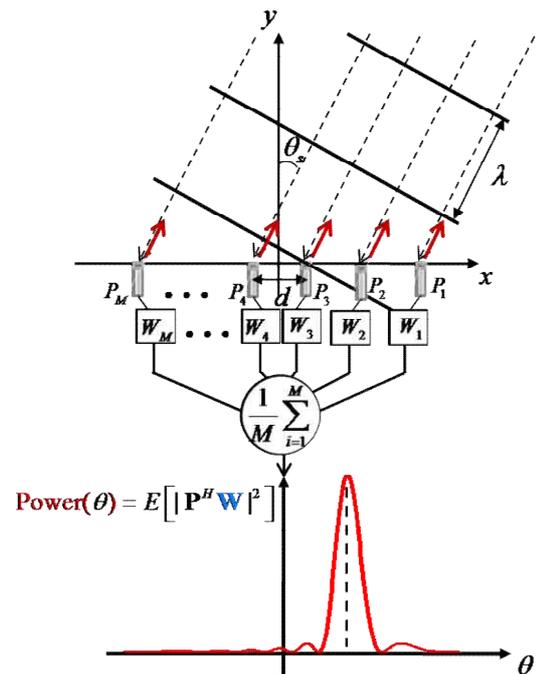


Figure 4. The principle of beamformer using a simple linear microphone array in frequency domain. A plane wave is propagating from $\theta = \theta_s$ direction and beam power has the maximum value when the scanning vector \mathbf{W} head the same direction with the incidence angle $\theta = \theta_s$.

Beam power has the maximum value when the scanning vector is equal to the phase difference between each microphone caused by the incident wave from $\theta = \theta_s$ direction. Then we can estimate the incident angle by finding the maximum value of beam power.

2.3 Beamformer with scattering effect

As mentioned chapter 2.2, beam power is obtained at each trial direction by steering the scanning vector \mathbf{W} and the estimation of the incident angle is carried out by finding the maximum value of beam power. In this procedure, the scanning vector \mathbf{W} plays an important role. It is needed to establish the appropriate sound propagation model and will affect to the incident angle estimation performance.

When we assume that there are no scatterers, there is only the incident sound field and the scanning vector can be selected as like equation (7) by using the incident sound field at each microphone attached on the surface of a rigid sphere.

$$\mathbf{W} = [W_1 \quad W_2 \quad \dots \quad W_M]^T$$

$$\text{where } W_i = \sum_{n=0}^{\infty} \sum_{m=-n}^n 4\pi i^n Y_n^m(\theta_i, \phi_i) j_n^{(1)}(ka) Y_n^m(\theta_{m,i}, \phi_{m,i}) \quad (7)$$

The equation (7) means the mathematical model of sound pressure at each microphone caused by a plane wave from the (θ_i, ϕ_i) direction. This scanning vector includes the phase difference between each microphone when a plane wave is incident from the (θ_i, ϕ_i) trial direction and thus the beam power has the maximum value when the trial direction (θ_i, ϕ_i) is equal to the direction (θ_s, ϕ_s) .

Unlike the earlier case, the effect of scattered sound field by a rigid sphere is included at each microphone and affect to the performance of the beamformer. In order to reflect the effect of scattered sound field, we have modified the scanning vector like equation (8).

$$\mathbf{W} = [W_1 \quad W_2 \quad \dots \quad W_M]^T$$

$$\text{where } W_i = \sum_{n=0}^{\infty} \sum_{m=-n}^n 4\pi i^n Y_n^m(\theta_i, \phi_i) \times \left(j_n^{(1)}(ka) - \frac{j_n^{(1)}(ka)'}{h_n^{(1)}(ka)} h_n^{(1)}(ka) \right) Y_n^m(\theta_{m,i}, \phi_{m,i}) \quad (8)$$

The modified scan function is the mathematical model of sound pressure at each microphone located on the surface of the rigid sphere and involves the scattered sound field as well as the incident sound field caused by a plane wave from the (θ_i, ϕ_i) direction.

3. PERFORMANCE ANALYSIS

3.1 Simulation condition

We have used the circular type microphone array mounted on the surface of the rigid sphere to see the impacts of scattering effect on the beamformer performance. As shown in Figure 5, the radius of the rigid sphere is choosed 0.15 m with considering the size of human's head and the array is composed of 20-microphones with equal space and a plane wave is incident from $(\theta_s, \phi_s) = (\pi/2, \pi)$. The frequency range of interest is from 300 Hz to 5 kHz. In this situation, we will compare the performance of beamformer for following cases.

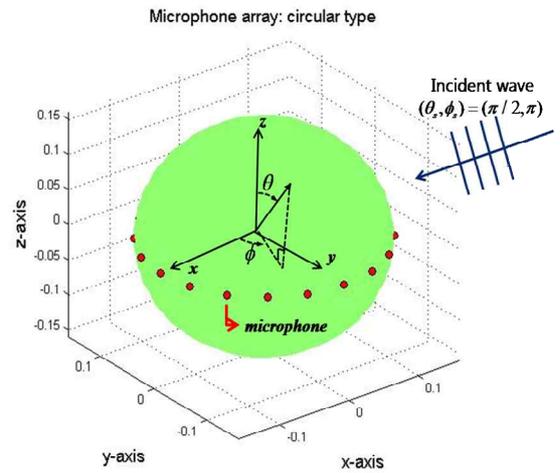


Figure 5. Conditions of simulation for beamformer performance. A circular type array composed of 20-microphones is attached on the surface of sphere and a plane wave is incident from the direction $(\theta_s, \phi_s) = (\pi/2, \pi)$

- Case 1: no scatterer in space (free-field case)
- Case 2: conventional beamformer(w/o scattering effect)
- Case 3: Beamformer w/ scattering effect

Performance of the beamformer can be mainly expressed by using the measure such as half-power bandwidth and maximum sidelobe level for each case. Half-power bandwidth and maximum sidelobe level are defined as Figure 6.

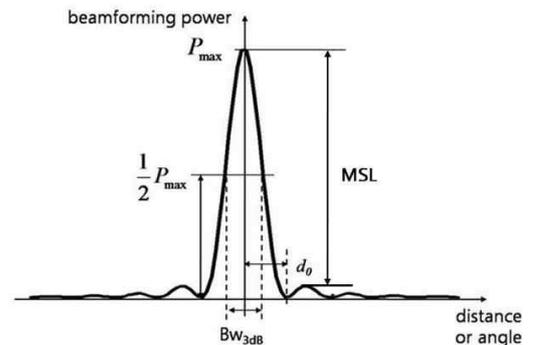
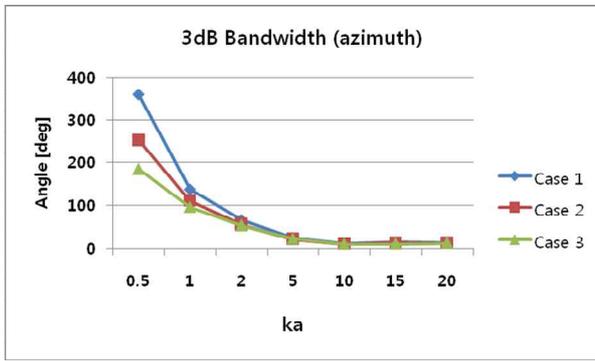


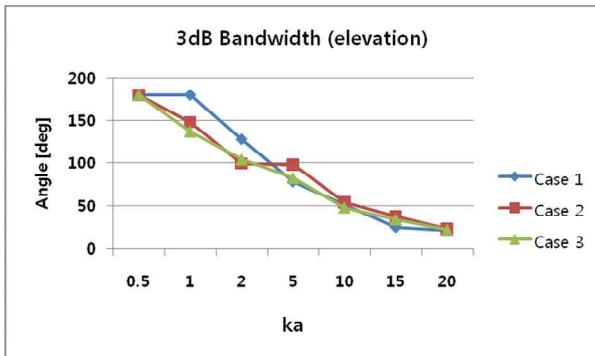
Figure 6. Definition of half-power bandwidth (BW_{3dB}) and maximum sidelobe level (MSL)

3.2 Half-power bandwidth

Figure 7 shows the result of the half-power bandwidth (BW_{3dB}) performance of beamformer for earlier 3-cases in session 3.1. According to the result, half-power bandwidth has similar trends in all cases and tends to become narrow as ka increases. In other words, the half-power bandwidth is mainly affected by ka (or the size of scatterer with respect to the wave length) not the scattering effect.



(a)



(b)

Figure 7. Result of the half-power bandwidth at each case (a) the half-power bandwidth of azimuth, (b) the half-power bandwidth of elevation direction

3.3 Maximum Sidelobe Level (MSL)

Figure 8 shows the result of the maximum sidelobe level in above 3-cases. The maximum sidelobe level experiences very little change as ka increases and the maximum sidelobe level of the third case has the highest value. Also, the maximum sidelobe level of conventional beamformer is lowered when the scattering occur.

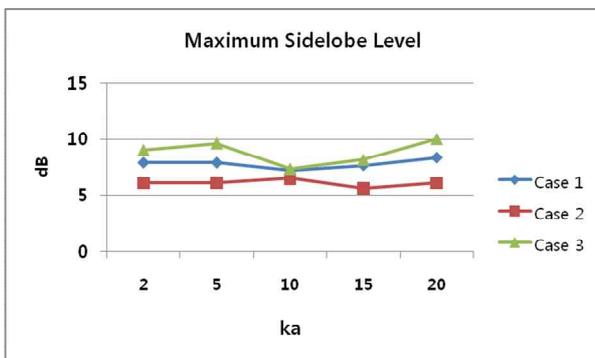


Figure 8. Result of the maximum sidelobe level at each case

4. CONCLUSION

We have discussed the performance of beamformer to see the effect of the scattered sound field by a scatterer on the result of visualization. It has been carried out by using the performance index such as half-power bandwidth and maximum sidelobe level. A circular array composed of the equally spaced 20-microphones was used in simulation when a plane wave is incident to a rigid sphere. Performance of beamformer was observed in three situations as follows: no scat-

terer in space (free-field case), conventional beamformer (w/o consideration of scattering effect) and beamformer w/ consideration of scattering effect. As a result of this study, half-power bandwidth has similar trends in all cases and tends to become narrow as ka increases. On the other hand, the maximum sidelobe level experiences very little change as ka increases and the maximum sidelobe level of the third case has the highest value. In addition, the maximum sidelobe level of beamformer is declined when the scattering occur. Also, we can see that it is possible to obtain the better performance of beamformer by using well-desinged scatterer from the result that third case has the best performance.

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