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

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PACS: 43.60.Jn

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.
2. BEAMFORMER WITH SCATTERING EFFECT

2.1 Scattering of a plane wave from rigid sphere

When a plane wave is propagated from \((\theta, \phi)\) 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

\[
P_{\text{tot}}(r, \theta, \phi) = P_{\text{inc}}(r, \theta, \phi) + P_{\text{sc}}(r, \theta, \phi),
\]

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

\[
P_{\text{inc}}(r, \theta, \phi) = \sum_{n=-\infty}^{\infty} \sum_{m=-n}^{n} 4\pi i^n Y_n^m(\theta, \phi) j_n(ka) Y_n^m(\theta, \phi).
\]

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

\[
P_{\text{sc}}(r, \theta, \phi) = \sum_{n=-\infty}^{\infty} \sum_{m=-n}^{n} 4\pi i^n Y_n^m(\theta, \phi) \cdot 
\left( \frac{j_n(ka)}{h_n(ka)} \right) Y_n^m(\theta, \phi).
\]

In the equation (2) and (3), the function \(Y_n^m(\theta, \phi)\) is defined as equation (4) and represents the spherical harmonics of order \(n\) and degree \(m\). In addition, the function \(j_n(ka)\) means the spherical Bessel functions of order \(n\), \(h_n(ka)\) is the spherical Hankel function of the first kind.

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

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

\[
P_{\text{tot}}(r, \theta, \phi) = \sum_{n=-\infty}^{\infty} \sum_{m=-n}^{n} 4\pi i^n Y_n^m(\theta, \phi) \cdot
\left( \frac{j_n(ka)}{h_n(ka)} \right) Y_n^m(\theta, \phi).
\]

Figure 3. Plane wave \((P_{\text{inc}}(r, \theta, \phi))\) propagation from \((r, \theta, \phi)\) direction and scattered sound field \((P_{\text{sc}}(r, \theta, \phi))\) by a rigid sphere with radius \(a\) in 3D view.

Figure 4. The principle of beamformer using a simple linear microphone array in frequency domain. A plane wave is propagating from \(\theta = \theta_0\) direction and beam power has the maximum value when the scanning vector \(\mathbf{W}\) head the same direction with the incidence angle \(\theta = \theta_0\).

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

\[
BP = |P^\mathbf{W}|^2 = |P, W|^2,
\]

where \(P = [P_1, P_2, \ldots, P_M]^T\) represent the \(M \times 1\) complex amplitude of the measured acoustic pressure vector and \(W = [W_1, W_2, \ldots, W_M]^T\) 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.
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 $\theta = \theta_0$ 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 $W$ and the estimation of the incident angle is carried out by finding the maximum value of beam power. In this procedure, the scanning vector $W$ 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.

$$W = \begin{bmatrix} W_1 & W_2 & \cdots & W_m \end{bmatrix}^T$$

where $W_i = \sum_{n=0}^{\infty} \sum_{m=-\infty}^{\infty} 4\pi i Y_n^m(\theta, \phi) Y_j^{1m} (\theta, \phi)$.

The equation (7) means the mathematical model of sound pressure at each microphone caused by a plane wave from the $(\theta_0, \phi_0)$ direction. This scanning vector includes the phase difference between each microphone when a plane wave is incident from the $(\theta, \phi)$ trial direction and thus the beam power has the maximum value when the trial direction $(\theta, \phi)$ is equal to the direction $(\theta_0, \phi_0)$.

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).

$$W = \begin{bmatrix} W_1 & W_2 & \cdots & W_m \end{bmatrix}^T$$

where $W_i = \sum_{n=0}^{\infty} \sum_{m=-\infty}^{\infty} 4\pi i Y_n^m(\theta, \phi) \times$

$$\left( Y_j^{1m}(ka) - \frac{Y_j^{0m}(ka)}{Y_j^{00}(ka)} - \frac{Y_j^{10}(ka)}{Y_j^{00}(ka)} \right) Y_n^m(\theta_0, \phi_0)$

The modified scanning vector 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 $(\theta, \phi)$ 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 chosen 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 $(\theta_0, \phi_0) = (\pi / 2, \pi)$. 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.

- 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.

#### 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.
**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.

**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 scatterer 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-designed scatterer from the result that third case has the best performance.

**ACKNOWLEDGEMENT**

This study is supported in part by the project of Agency for Defence Development (ADD-07-07-01), Korea Atomic Energy Research Institute (KAERI), Korea Railroad Research Institute(KRRI), Brain Korea 21 project, and the Conversing Research Center Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2009-0082296).

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