Sound manipulation: Theory and Applications
음장 제어의 이론과 그 적용

Yang-Hann Kim

김 양 한

Key Words : sound manipulation, impedance mismatch, acoustic contrast control

ABSTRACT

Sound manipulation is to control sound field using multiple sound sources for appropriate purposes. In linear acoustics, a sound can be constructed by superimposing several fundamental sound fields such as a planewave and sphere shape sound field. That is how we manipulate sound field. In this paper, we introduce the theory of sound manipulation and its applications from the examples of the generation of fundamental sound field: a circle, a ring shape sound field and a planewave field.

1. Objective

Sound waves propagate in space and time. How sound wave propagates depends entirely on the spatial characteristics of impedance. The impedance can be characteristic impedance of medium or the boundary impedance that describes how the sound reflected, scattered, diffracted, refracted, or transmitted. This implies that we can also manipulate sound waves by controlling impedance in space. Simple example would be the sound waves, propagating in a wave guide, which is bounded by a rigid wall that has infinite impedance.

If the wave guide has a rigid wall and whose diameter is much smaller than the wave length of interest, then the sound emitted at the one end can be heard without any distortion at the other end of the wave guide. This simple example implies that if we can make the wave guide in space, then we can transmit the sound at the place of which we want. This means that the wave guide can generate the quite zone, where we can not hear sound and where we can hear the sound; bright zone. To implement this physical observation in practice, we have to find out the way to make a wave guide in space, on other words making rigid wall in space that we want; big impedance mismatch in space.

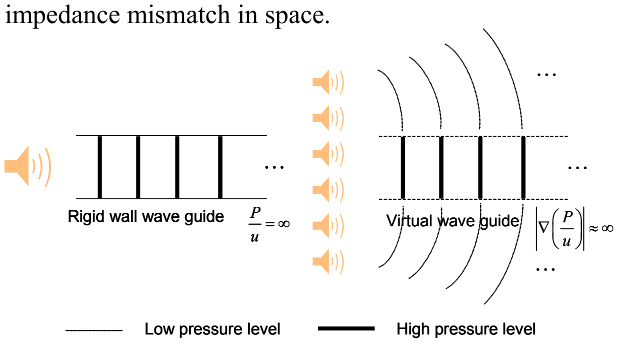

Figure 1. A wave guide with rigid wall (left) and a virtual wave guide by generating impedance mismatch in space (right)

The impedance mismatch in space can be accomplished by using many secondary sound sources as illustrated in Fig. 1. In fact, Huygen's principle or Kirchhoff-Helmholtz integral equation essentially implies the method to make such impedance mismatch in space for a selected frequency.

We can also extend this idea to make any shape of sound field in space. For example, we can try to make a sphere in space. In other words, the sphere with radius a , and contains relatively high acoustic potential energy. This can be achieved by using multiple sound sources that has the desired radiation impedance at the surface that we define (Fig. 2). We can also attempt to control acoustic impedance in space and intensity distribution.

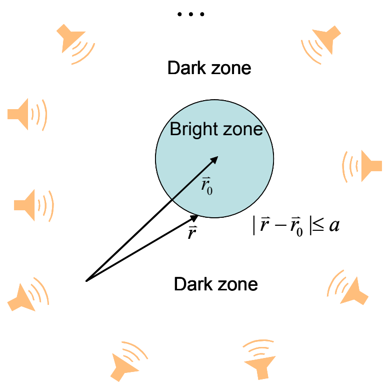

Figure 2. Sound shape control in space

Having these elementary sound fields would lead us to manipulate sound in space. In other words, we can draw sound picture as we want in space by using multiple sources. This is our major objective of study.

2. Problem definition

Our problem definition to implement the idea for manipulating sound in space and time is related to generate or make sound that we want by using finite number of sound sources. The issues are, therefore,

---

† Regular member, Center for NOise and VIbration Control (NOVIC), Dept. of Mechanical Engineering at KAIST
E-mail: yanghannkim@kaist.ac.kr
Tel: (042) 869-3025, Fax : (042) 869-8220

related with the way to implement "generation of sound" and find out the effect of "finite number of sound sources." The former is analogous to design a fundamental or representative means of sound. There is, in principle, infinite number of ways to have such sound field. To begin with, we attempt to start with two fundamental sound fields. One is plane wave and the other is spherical shape sound field in space. The sphere can have any diameter, frequency, and location. The plane wave can have arbitrary propagation constant, in other words, direction. Fig. 3 essentially depicts the main idea to manipulate sound in space using these fundamental sound fields.

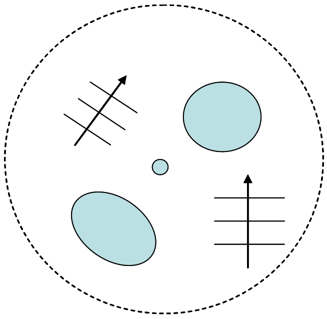

Figure 3. Sound manipulation: linear superposition of fundamental sound fields

2.1 Generation of a sphere sound shape in space

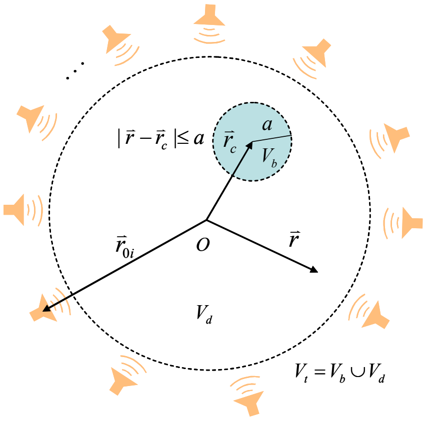

Figure 4. System configuration for sound shaping

As shown in Fig. 4, if we consider a sphere sound shape in a total zone of interest V_t, desired sound shape can be expressed as

$$p_d(\vec{r};\omega) = \frac{H(|\vec{r}-\vec{r}_c|) - H(|\vec{r}-\vec{r}_c|-a)}{4\pi a^2} \tag{1}$$

where H is Heaviside function ($|\vec{r}-\vec{r}_c| \le a, \vec{r} \in V_t$). In this case, the region satisfying the condition $|\vec{r}-\vec{r}_c| \le a$ becomes a bright zone and the other region in V_t becomes dark zone. On the other hand, the sound field induced by multiple sources is expressed as

$$p_c(\vec{r};\omega) = \sum_{i=1}^{N} h(\vec{r}\,|\,\vec{r}_{0i};\omega)s_{i;\omega} \tag{2}$$

where h is a transfer function between source position $\vec{r}_{0i}$ and field position $\vec{r}$, $s_{i;\omega}$ is a source input for a specific frequency, and N is the number of sources. In this case, the average of acoustic energy for a specific zone V is determined as a representative parameter for the control and it is expressed as

$$\begin{aligned} e &= \frac{1}{V}\int_V p_c(\vec{r};\omega)^* p_c(\vec{r};\omega)dV \\ &= \mathbf{s}^H \left(\frac{1}{V}\int_V h(\vec{r}\,|\,\vec{r}_{0i};\omega)^* h(\vec{r}\,|\,\vec{r}_{0i};\omega)dV \right)\mathbf{s} = \mathbf{s}^H \mathbf{R}\mathbf{s} \end{aligned} \tag{3}$$

where $\mathbf{R}$ is spatial correlation matrix and $\mathbf{s}$ is a source input vector. To find the optimal source input for each source, if we choose a cost function $\beta (= e_b / e_d \text{ or } e_b / e_t)$ to maximize averaged acoustic potential energy ratio between the bright zone and dark zone: acoustic contrast, then this problem becomes a maximum eigenvalue problem [1].

$$\mathbf{R}_d^{-1}\mathbf{R}_b\mathbf{s} = \beta\mathbf{s} \tag{4}$$

Obtaining the appropriate eigenvector for a maximum eigenvalue, we can easily find the optimal source input for a frequency and we can make a sphere sound shape.

2.2 Generation of a planewave field

For 2-dimention case, a planewave propagating on $z = 0$ plane can be expressed as a delta function in wavenumber domain according to spatial Fourier transform as shown in Fig. 5. We can also expand this idea to 3-dimension case and this can be considered as a wavenumber domain focusing problem or wavenumber domain shaping problem [2]. In this case, how to get the optimal source input for making a planewave field is the same as the procedure previously mentioned except for the change of domain that we are interested in: wavenumber domain.

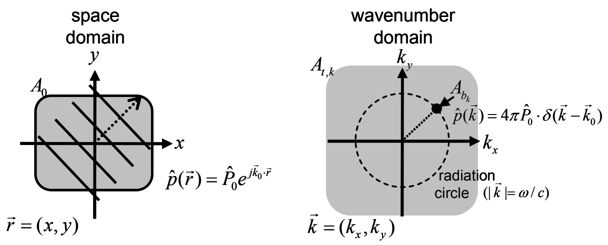

Figure 5. Representation of a plane wave in space and wavenumber domain. **(left)** space domain, A_0 : control zone in space domain, **(right)** wavenumber domain, A_{b_k} , A_{t_k} : bright zone and total zone of interest in wavenumber domain.

3. Examples

As mentioned in problem definition, let us make several sound fields as an example. In this case, for the simple cases, we consider 2 dimensional sound field generation ($z=0$ plane) and use polar coordinate system: r, θ to describe sound field. But sound sources can be located everywhere except for the position in total control zone.

3.1 Sound shaping: circle shape sound field

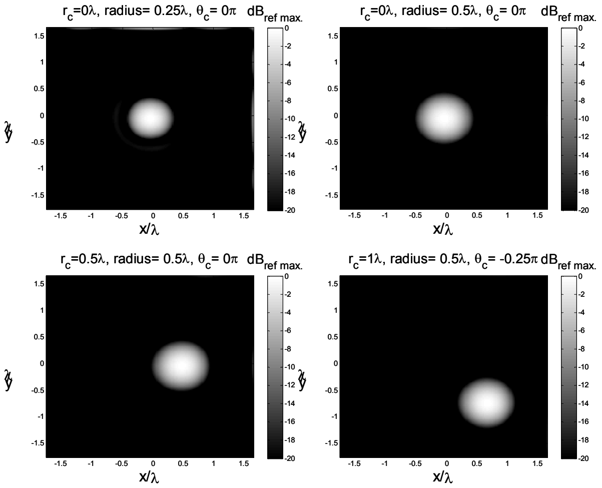

Figure 6. Control results for circle sound shape generation

(top left) $\vec{r}_c = (0,\theta)$, $a = \lambda/4$

(top right) $\vec{r}_c = (0,\theta)$, $a = \lambda/2$

(bottom left) $\vec{r}_c = (\lambda/2, 0)$, $a = \lambda/2$

(bottom right) $\vec{r}_c = (\lambda/2, -\pi/4)$, $a = \lambda/2$.

Mathematically, a circle sound shape can be expressed as

$$p_d(\vec{r};\omega) = \frac{H(|\vec{r}-\vec{r}_c|) - H(|\vec{r}-\vec{r}_c|-a)}{2\pi a} \tag{5}$$

where $\vec{r}$ is (r,θ). If we take acoustic contrast control for predefined bright zone and dark zone, we can observe whether the center of a circle and its radius are controllable as shown in Fig. 6. In this simulation, for every 15° elevation angle from -90° to 90°, 24 sources are arranged with the equal angle difference in θ-direction. From these results, we have obtained over 20dB sound pressure level difference between bright zone and dark zone.

3.2 Sound shaping: ring shape sound field [3]

A ring shape sound field can be expressed as

$$p_d(r,\theta) = \frac{\delta(r-r_0)}{2\pi r} \tag{6}$$

where r_0 is a radius of a ring. In this example, 12 sources are distributed in θ-direction with the same angle difference 15° for each φ_s as shown in Fig. 7(left top) and the total control zone is bounded by the circle with the radius 1m. In Fig. 7, we can observe ring shape field with $r_0 = 0.2m$ even though there are side lobes, which can be reduced by adding control sources.

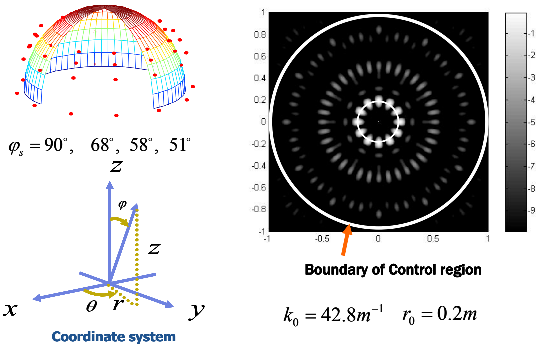

Figure 7. **(left top)** dots: source position **(left bottom)** coordinate system **(right)** the result of ring sound shape generation

3.3 Planewave generation [2]

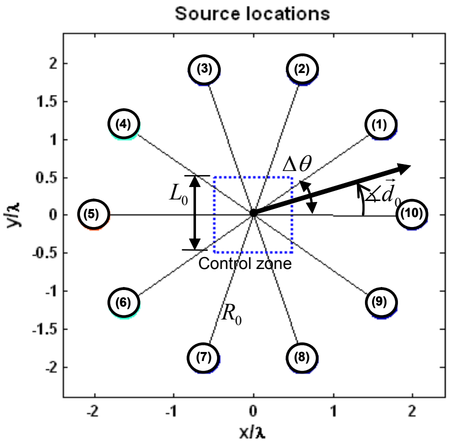

Figure 8. Configuration of sources and zone for wavenumber domain focusing. L_0 : aperture size of control zone(A_0), $\measuredangle\vec{d}_0$: angle of the control direction, r_0 : distance of the sources from origin, $\Delta\theta = 2\pi / N$: angular interval between the sources, N : number of sources.

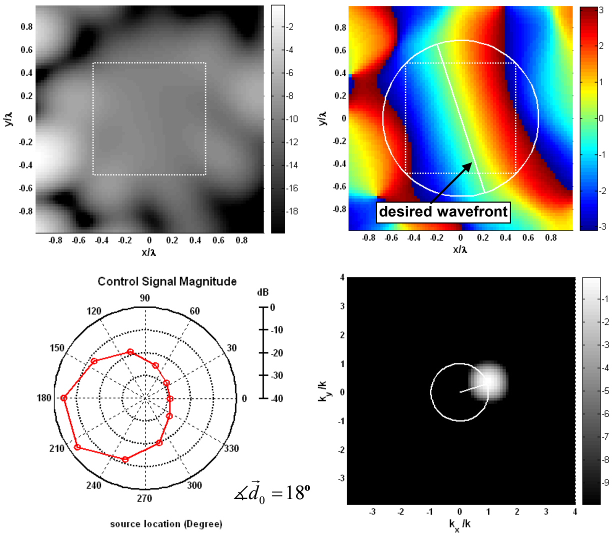

Figure 9. **(top left)** Magnitude distribution of the controlled sound field **(top right)** Spatial phase change of the controlled sound field. [Solid line: desired wave front, Dotted line: control zone)] **(bottom left)**Input power distribution according to each control direction **(bottom right)** Wavenumber spectrum of the controlled sound field. [Magnitude scale is normalized by the peak value.]

. In this example, 12 monopole sources were positioned at the same distance($R_0 = 2\lambda$) from the origin. Because the listener should have the freedom to face any direction, the sources were distributed with the same angular distance($\Delta\theta$). The control zone was configured as a plane of finite aperture $L_0 = \lambda$. Fig. 9 shows a planewave field with the incident angle $\measuredangle\vec{d}_0 = 18^\circ$

4. Conclusions

We have introduced the theory and its applications in sound manipulation from the mathematical formulations and examples. We can make sound field we want with combination of fundamental sound fields as mentioned in the main text. Also these technologies are realistic and the noticeable results were reported for sound focused personal audio system [4]. In the near future, we would experience the advantage of sound manipulation technologies in various fields such as personal audio system and therapeutic ultrasound.

Acknowledgement

This work was supported by the Korea Science and Engineering Foundation(KOSEF) through the National Research Lab. Program funded by the Ministry of Science and Technology(R0A-2005-000-10112-0).

References

(1) J.-W. Choi, Y.-H. Kim, 2002, “Generation of an acoustically bright zone within an illuminated region,” J. Acoust. Soc. Am. Vol. 111(4), pp. 1695-1700.

(2) J.-W. Choi, *Spatial Manipulation and Implementation of Sound*, Doctorial Thesis at KAIST, 2005.

(3) J.-Y. Park and Y.-H. Kim, "Shaped sound focusing using multiple sources: An acoutical ring," 152nd meeting, Acoustical Society of America, Sheraton-Waikiki Hotel, Honolulu, Hawaii, 28 Nov-2 Dec.

(4) C.-H. Lee, J.-H. Chang, J.-Y Park, and Y.-H Kim, “Personal sound system design for mobile phone, monitor, and television set; Feasibility study,” 154th meeting, Acoustical Society of America, Sheraton New Orleans Hotel, New Orleans, Louisiana, 27 Nov.-1 Dec. 2007, 4aEA4.