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Generation of a private listening zone; acoustic parasol

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ABSTRACT

Recently there are several studies for providing a private listening zone to users such as private audio system and active headrest in aircraft. The objective of these researches is to make louder sound at a zone comprising the listeners (acoustically bright zone), and reduce the sound elsewhere (acoustically dark zone). Acoustic contrast control can be a good way to achieve the objective because it maximizes the ratio of acoustic potential energy density between acoustically bright zone and dark zone. As an application of this research, we have attempted to generate a private listening zone in the case of a dining table with parasol. More than one user is sitting around the table, and loudspeakers are arranged on the bottom side of parasol; acoustic parasol. Zone of interest is determined around the table. A circular loudspeaker array is used for making ring-shaped bright zone except the table. Therefore, the table and outside of the bright zone is determined as the dark zone. In order to determine several control variables with related to the loudspeaker arrangement and evaluate the performance of the acoustic parasol, computer simulations are carried out. The results are compared with those of the experiments.

1. INTRODUCTION

In recent years, several researches have been carried out for providing a private listening zone to users by localizing sound only around the listeners using multiple loudspeakers. For example, Chang *et al.* realized a private audio system which used a linear array speaker[2]. Elliott and Jones suggested an active headrest which makes it possible to provide a private listening zone for the passengers in aircraft using loudspeakers on the headrest[3]. Besides, generation of private listening zone can be applied to various cases[4].

For one case, we consider that people in public places such as a café and a restaurant listen to the same music given for every customer although some of them may be disturbed by the music. In this study, therefore, a parasol which is commonly used in public places is suggested to provide a private listening zone for users sitting around a table using multiple loudspeakers: acoustic parasol. (Figure 1) We use a set of loudspeakers arranged in circular shape above the desired zone, and provide the private listening zone for several users around a table at the same time.

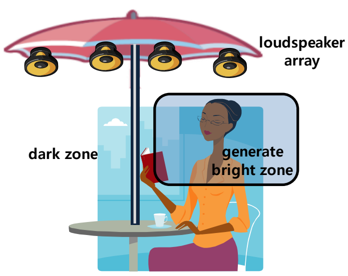


Figure 1. The description of the acoustic parasol

The objective of this study is to enhance acoustic energy only around a table using multiple loudspeakers and to investigate the feasibility for use of acoustic parasol. For this purpose, we need to enhance the sound energy at the zone where the listeners are supposed to be (acoustically bright zone), and reduce the sound energy at the zone elsewhere (acoustically dark zone). It is realized by acoustic contrast control which was suggested in 2002 by Choi and Kim[1]. This method is to maximize the acoustic energy density ratio between acoustically bright zone and dark zone.

In Section 2, acoustic contrast control is explained briefly as a theoretical background. In Section 3, acoustic contrast control is applied to acoustic parasol, and the system setup is described regardless of the loudspeaker arrangement: the number of loudspeakers and the size of loudspeaker array. In Section 4, a method to determine the loudspeaker arrangement by iterative computer simulation is presented. In Section 5, the acoustic parasol is realized with the determined parameters in Section 4. In order to verify the system, experiments are carried out, and we compare the results with those of the computer simulation.

2. THEORETICAL BACKGROUND: ACOUSTIC CONTRAST CONTROL

Acoustic contrast control provides an optimal filter ($s_m(\omega)$) that maximizes the acoustic energy ratio of the bright zone V_b to the dark zone V_d (or the total zone of interest V_t), as shown in Figure 2. This makes it possible to generate an acoustically focused region in space.

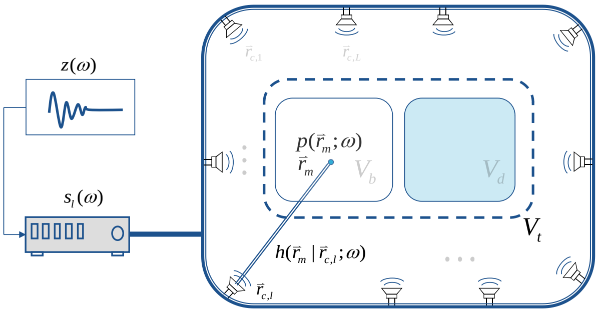


Figure 2. System configuration for acoustic contrast control (z : input signal, s_l : filter coefficient of multi-channel filter, h : transfer function, $\vec{r}_m$: field position vector, $\vec{r}_{c,l}$: l -th source position vector, L : number of sound source, V_b : volume of bright zone, V_d : volume of dark zone, V_t : volume of the total zone of interest)

In Figure 2, the pressure at a position $\vec{r}_m$ when the sound sources are located at $\vec{r}_{c,l}$ (l = 1, 2, …, L) is expressed as

$$p(\vec{r}_m;\omega) = \sum_{l=1}^{L} h(\vec{r}_m \mid \vec{r}_{c,l};\omega) s_l(\omega) z(\omega) \\ = \mathbf{h}(\vec{r}_m \mid \vec{\mathbf{r}}_c;\omega)\mathbf{s}(\omega) z(\omega) \quad (1)$$

If we consider a pressure vector $\mathbf{p}_b$ in V_b , then we can be expressed as

$$\mathbf{p}_b = \mathbf{h}_b \mathbf{s} z \,, \quad (2)$$

where $\mathbf{p}_b = \left[p(\vec{r}_{b,1};\omega) \quad \cdots \quad p(\vec{r}_{b,M_b};\omega) \right]^T$, M_b is the number of discretized points in the bright zone V_b and $\mathbf{h}_b = \left[h(\vec{r}_{b,1} \mid \vec{\mathbf{r}}_c;\omega) \quad \cdots \quad h(\vec{r}_{b,M_b} \mid \vec{\mathbf{r}}_c;\omega) \right]^T$, which is a transfer function matrix between loudspeakers and the field positions in the bright zone. The spatial average of acoustic energy for the bright zone is then expressed in matrix form as

$$e_b = \frac{|z|^2}{M_b} \mathbf{s}^H \mathbf{h}_b^H \mathbf{h}_b \mathbf{s} \,. \quad (3)$$

Similarly, it is also possible to calculate the spatial average of the acoustic energy for the total zone of interest V_t . A cost function for optimization is defined here as the acoustic energy ratio of the bright zone to the total zone of interest; in other words, it is the acoustic contrast:

$$\beta = \frac{M_{d \text{ or } t}}{M_b} \frac{\mathbf{s}^H \mathbf{h}_b^H \mathbf{h}_b \mathbf{s}}{\mathbf{s}^H \mathbf{h}_{d \text{ or } t}^H \mathbf{h}_{d \text{ or } t} \mathbf{s}} \quad (4)$$

In Eq. (4), the optimal filter which maximizes the acoustic contrast β is simply given as the eigenvector corresponding to the maximum eigenvalue of $(\mathbf{h}_{d \text{ or } t}^H \mathbf{h}_{d \text{ or } t})^{-1} \mathbf{h}_b^H \mathbf{h}_b$. Finally the energy ratio between the bright zone and the dark zone can be maximized for a single input signal.

3. PROBLEM DEFINITION: DESIGN PROBLEM

Let us suppose that people sit around a circular table with acoustic parasol, and we want to make sound louder only around them. To apply contrast control in this situation, we determine several kinds: the band of frequencies of interest, the zone of interest (the bright zone and the dark zone), and the loudspeaker arrangement.

First, we select three frequencies at one octave band of frequencies which center frequency is 1000 Hz: 800 Hz, 1000 Hz, and 1200 Hz, because the sound from this band is listenable to human. Furthermore, since one of the objectives in this study is carrying out a feasibility study for use of acoustic parasol, we consider frequencies in only one ocatave band for contrast control.

Second, the zone of interest is positioned at the same plane with the user's ear position, and it is square plane which dimension of each length is 1.6 m. (Figure 3(a)) Let us define the shape of the bright zone as a ring considering the movement of head is needed, because people are around the table and the area of the table is not contained in the bright zone. Pondering the size of human's head (which is about 0.24 m) and its' movement, the difference between the outer and inner radius of the bright zone is 0.3 m. Because a diameter of common table is 0.6 m, it can be determined that the inner radius of the bright zone is 0.3 m, then the outer radius becomes 0.6 m. The dark zone is all region of the total zone except the bright zone.

Third, since the shape of the bright zone is ring-shape, the shape of the arrangement is determined as a circle. This circular loudspeaker array is attached on the bottom side of the parasol, and it is 1 m away from the subject's ear position, namely, the height of the circular loudspeaker array is 1 m. Figure 3 shows the relationship between zones and the circular loudspeaker array.

Because the number of loudspeaker and the size of the circular loudspeaker array significantly influence to control results, we need to choose optimum values of them.

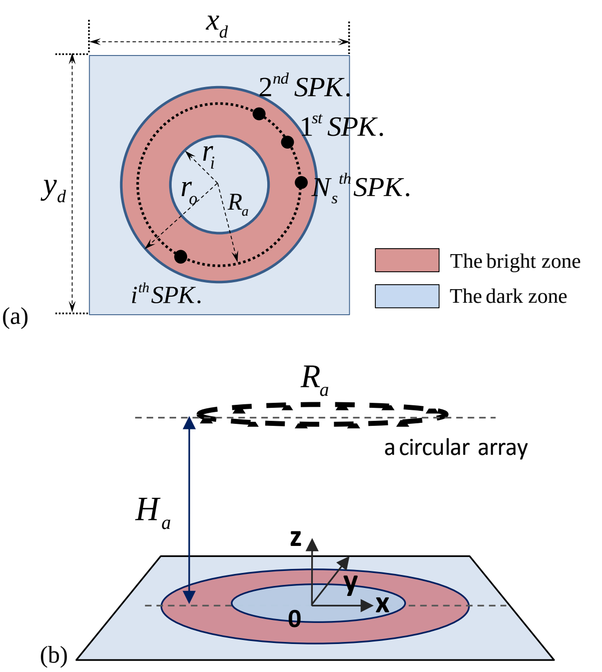


Figure 3. The system setup (a) The bright zone and the dark zone (r_o and r_i : the outer and the inner radius of bright zone, x_d and y_d : the dimension of total zone, N_s : the number of loudspeaker, R_a : the radius of the circular loudspeaker array, H_a : the height of the circular loudspeaker array from the subject's ear). (b) Three-dimensional description of the zone of interest and the circular loudspeaker array.

4. SOLUTION METHOD

As a solution method which determines the number of loudspeaker and the radius of the circular loudspeaker array, parametric study is carried out by computer simulation. That is, by changing these parameters and calculating the performance of the acoustic parasol, we find a couple of values which results in effective performance: the largest contrast with the minimum number of loudspeakers.

Let us consider the design for computer simulation. Control zone is a plane, and it is discretized by the spacing Δx and Δy . The spacing is selected to be 0.04 m which is about 1/7 of minimum wavelength of interest (wavelength of 1200 Hz), because we can see more precisely in computer simulation. Moreover, we assume that each loudspeaker behaves as a monopole in free-field. Like in Section 3, monopole sources are located to be 1 m away from the control plane, and arranged in a circle. A method for determining the number of loudspeaker and the radius of the circular loudspeaker array is used in three selected frequencies: 800 Hz, 1000 Hz, and 1200 Hz.

4.1 Loudspeaker arrangement

In order to determine loudspeaker arrangement, we consider the effects of the number of loudspeaker and the radius of circular loudspeaker array. Since it is necessary to find the optimal N_s and R_a which make the maximum contrast by using the minimum number of loudspeaker.

Figure 4 shows the contrast in decibel scale with respect to the normalized radius of circular loudspeaker array (normalized by each wavelength) at three selected frequencies: 800 Hz, 1000 Hz, and 1200 Hz. In this case, the number of loudspeaker is twelve. As illustrated in Figure 4, three graphs of contrast in each frequency appear similar trend. As frequency increases, however, the maximum contrast tends to be shifted to the left side. It means that the smaller radius of circular loudspeaker array is necessary at higher frequency. From Figure 4, the radius having the maximum averaged contrast (averaged in the cases of three frequencies) is about 0.5 m, and we determine this value as the radius of the array.

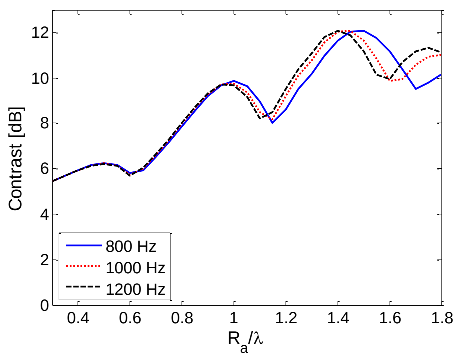


Figure 4. The contrast with respect to normalized radius of circular loudspeaker array in the selected frequencies: 800 Hz, 1000 Hz, and 1200 Hz. The number of loudspeaker is twelve. (R_a : the radius of circular array, λ : wavelength)

Figure 5 shows the normalized contrast (normalized by the maximum value of contrast) with respect to the normalized loudspeaker spacing Δ (Eq. (5)), which is normalized by each wavelength of the selected frequencies.

$$\Delta = \frac{2\pi R_a}{N_s} \tag{5}$$

where the radius of circular loudspeaker array R_a is 0.5 m. In Figure 5, the normalized contrast converges in certain value of spacing. Let us define that convergence begins from 0.95 of the normalized contrast (95% of the maximum contrast). More loudspeakers correspond to smaller spacing in the same radius of circular loudspeaker array. Therefore, it is effective to select the smallest number of loudspeaker under convergence in the selected frequencies.

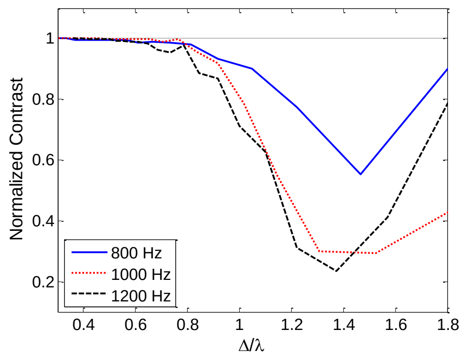
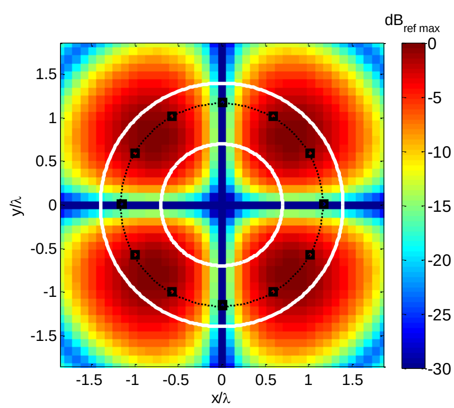


Figure 5. The normalized contrast with respect to normalized loudspeaker spacing in the selected frequencies: 800 Hz, 1000 Hz, and 1200 Hz. The contrast is normalized with maximum value. The radius of circular loudspeaker array is 0.5 m. (Δ : loudspeaker spacing, λ : wavelength)

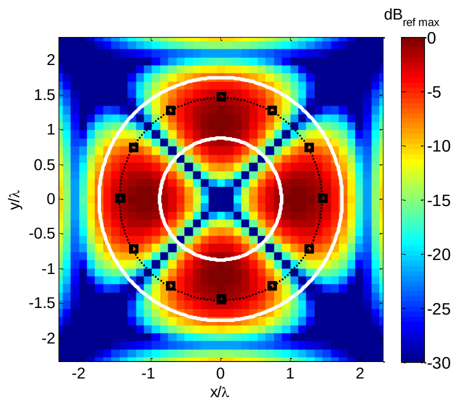
As a result, the loudspeaker arrangement is determined with twelve loudspeakers and 0.5 m radius. Therefore, we can get the expected performance, which means that every normalized contrast is above 0.95 in the entire frequency range of interest. (For your guidance, when 0.5 m of circular loudspeaker array radius is determined with 10 loudspeakers, every normalized contrast is not above 0.95.)

4.2 Control results

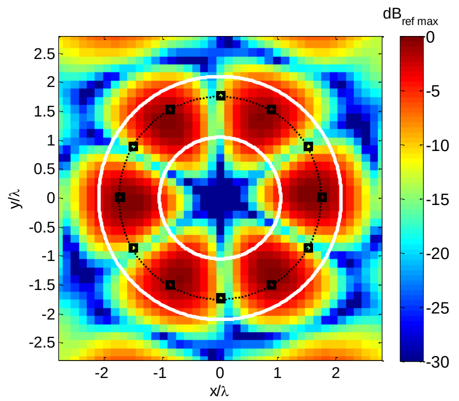
Figure 6(a)-(c) shows the magnitude distribution of sound pressure after contrast control via loudspeaker arrangement determined in Section 4.1 in decibel scale at each frequency. Because reference is the maximum value in decibel scale, 0 dB means the maximum value of the sound pressure magnitude. Every dimension of the total zone is normalized with wavelength. The contrasts are about 7.9 dB, 12.0 dB, and 11.3 dB, respectively. As illustrated in Figure 6(a)-(c), acoustic energy is focused symmetrically on the four regions at 800 Hz and 1000 Hz, and on the six regions at 1200 Hz. (Each focused region can be considered to the private listening zone.) That is, as frequency decreases, more loudspeakers are used to generate one focused region.



(a)



(b)



(c)

Figure 6. The pressure distribution after contrast control due to the determined loudspeaker arrangement in decibel (reference to maximum value) scale in the selected frequencies; every dimension of the measurement plane is normalized with wavelength: (a) 800 Hz (b) 1000 Hz (c) 1200 Hz.

Let us assume that the magnitude and phase of input signal fed into the loudspeaker is linearly related to those of the pressure generated by loudspeaker. Therefore, we can consider the implication between the calculated input signals and the shape of the pressure field which is generated after contrast control.

Figure 7 depicts the magnitude and phase of the optimized input signals of each loudspeaker after contrast control at the selected frequencies. Loudspeakers positioned above bright zone have larger magnitude than those of loudspeakers positioned above the middle of the bright zones. For example, no signals are fed into the loundspeakers # 3, 6, 9, and 12 at 800 Hz, but the same speakers have larger magnitudes than those of the others at 1000 Hz. Moreover, even number of loudspeaker has larger magnitudes than those of the others at 1200 Hz. Input signals of loudspeakers which contribute to generate a sound focused region are out of phase with the input signals of loudspeakers for the adjacent focused region. For example, loudspeakers # 1 and 2 generate out of phased pressure with those given by loudspeakers # 4 and 5 at 800 Hz. Therefore, according to the magnitude and phase of input singals fed into each loudspeaker, bright zone is divided to several regions. Besides, the magnitude and phase of the input signals appear symmetrically following the symmetric shape of the sound pressure distribution.

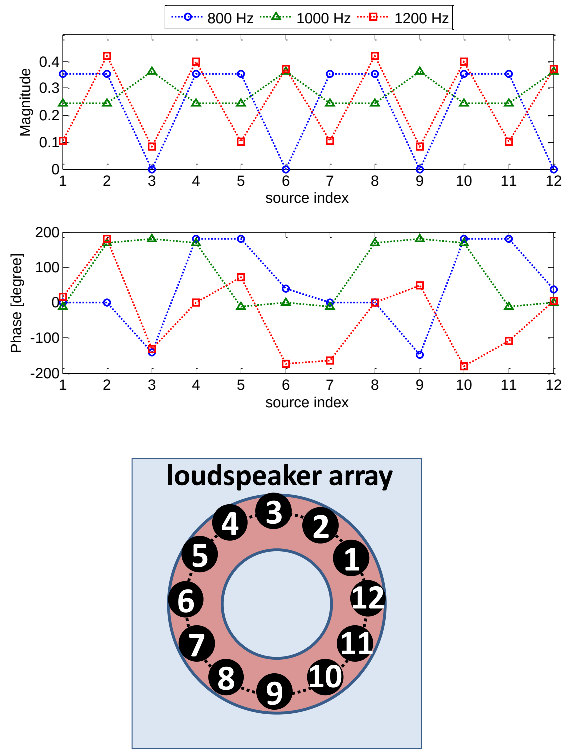


Figure 7. Magnitude and phase of the optimized input signals fed into each loudspeaker at selected frequencies: 800 Hz, 1000 Hz, and 1200 Hz

5. THE REALIZATION OF AN ACOUSTIC PARASOL

In order to verify the system with the determined parameters (the number of loudspeakers and the size of circular loudspeaker array) and compare with the results of computer simulation in Section 4, an experiment was carried out. We considered a circular loudspeaker array which radius is 0.5 m and consists of twelve loudspeakers. The experiment was done in an anechoic chamber at KAIST (3.6^W m × 3.6^L m × 2.4^H m, 100 Hz cutoff frequency) in a free field condition. Furthermore, we assume that there is no scattering effect by head of the user and a table.

5.1 Experimental setup

Figure 8 briefly decribes control zone and a circular loudspeaker array. Let us suppose that we can change direction of the system as depicted in Figure 8 because the experiment is carried out in an anechoic chamber. To compare with the results of the computer simulation in Section 4, the same geometric information of control zone in the case of computer simulation is selected. As a feasibility study, we consider only the plane which user's ear can be commoly positioned. Therefore, the shape of control zone (the measurement plane) is a square which dimension is 1.6 m × 1.6 m. Ring shaped bright zone has 0.3 m inner radius and 0.6 m outer radius considering movement of user's head which size is generally about 0.24 m. The other zone is dark zone. A circular loudspeaker array is positioned 1 m away from the measurement plane.

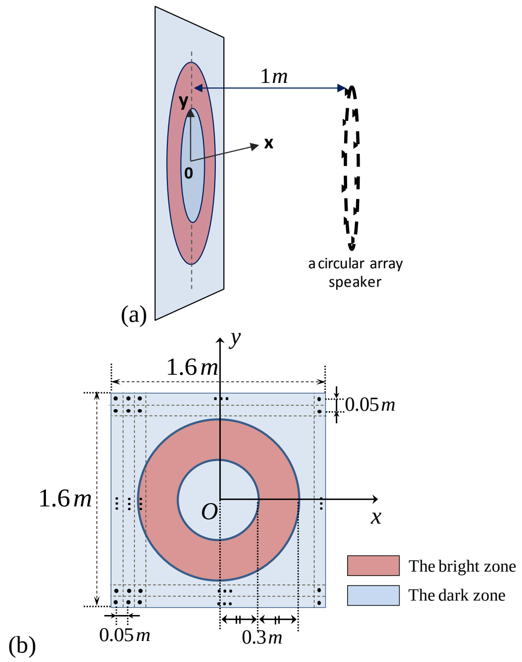


Figure 8. Control zone and a circular loudspeaker array; direction of the system is turned around different to in the case of computer simulation because the experiment is carried out in an anechoic chamber. (a) Brief description of experimental setup (b) Discretized measurement plane

Figure 9 shows a setup of loudspeaker and microphone array. As shown in Figure 9, twelve loudspeakers are arranged in a circular shape with 0.5 m radius. We assume that the effect of the parasol is negligible because the loudspeakers are headed forward the measurement plane which is opposite direction of the parasol. Figure 10 depicts frequency response function and coherence function between the input voltage signal into a loudspeaker and the output pressure signal which is measured at a point 1 m ahead. Figure 10(b) indicates that the loudspeaker is workable in frequencies of interest (800 Hz ~ 1200 Hz) because the coherence function is unity in the range.

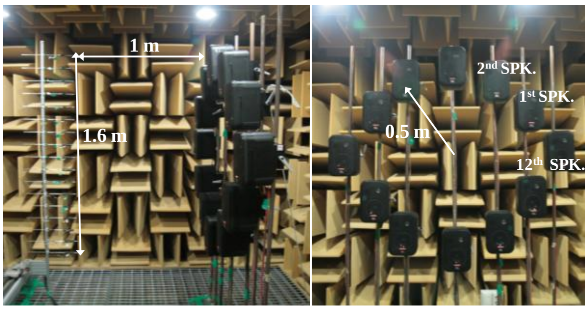
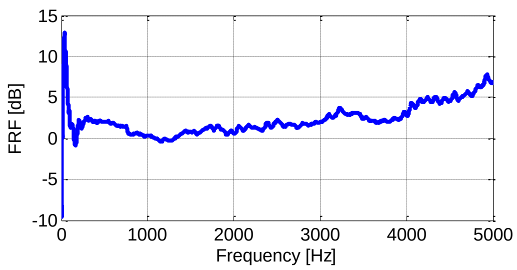
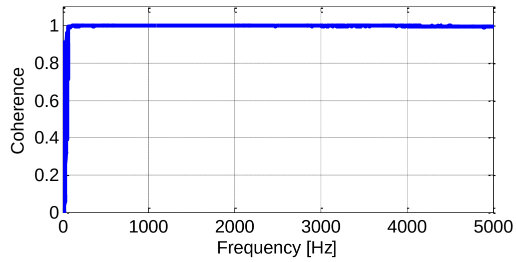


Figure 9. The loundspeaker and microphone array; 17 microphones are arranged in a vertical line with 10 cm equal spacing. A circular loudspeaker array has twelve loudspeakers with 0.5 m radius.



(a)



(b)

Figure 10. Frequency response function and coherence of a loudspeaker; the loudspeaker is workable in frequencies of interest (800 Hz ~ 1200 Hz). (a) Frequency resoponse function (b) Coherence function

5.2 Transfer function measurement

The transfer functions are measured by a microphone array (Figure 9) in the measurement plane. We used array microphones (B&K type 4935). The measurement spacings are determined to be 0.05 m, which is about 1/5 of the minimum wavelength of interest (wavelength of 1200 Hz) to avoid spatial aliasing at the frequency. Since we used 17 array microphones, the microphone array is spaced by 0.1 m. In total, therefore, 66 steps (2 steps in vertical axis and 33 steps in horizontal axis) of measurements were performed.

We used a sine sweep signal for the input signal, which frequency is sweeping by 4000 Hz linearly. This signal is playbacked through following parts: PC, multi-channel sound cards (Echo Audiofire 12), multi-channel audio amplifier (Yamaha RX-V659), and the circular loudspeaker array.

At selected frequencies: 800 Hz, 1000 Hz, and 1200 Hz, we have the transfer functions $\mathbf{h}(\vec{r}_m\,|\,\vec{\mathbf{r}}_c;\omega)$ at all measurement points (33 × 33 points). Figure 11 shows the absolute value of transfer function by the first loudspeaker. From this transfer function matrix, we obtain the contrast control solution by solving the eigenvalue problem as explained in Section 2.

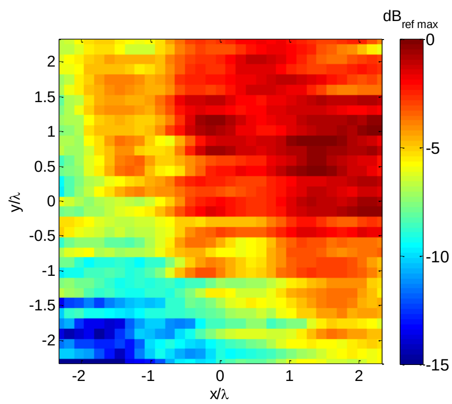
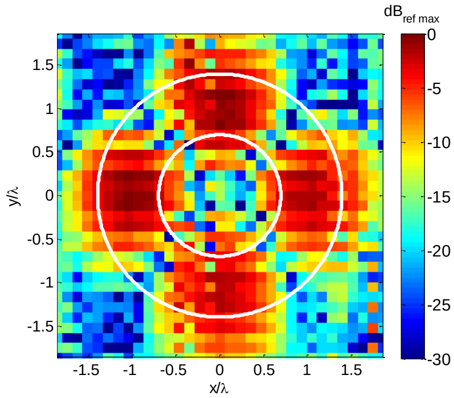


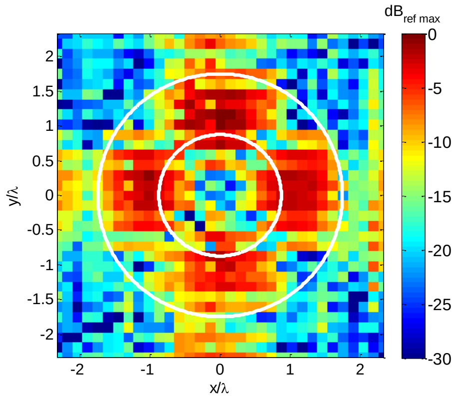
Figure 11. Absolute values of transfer function by the first loudspeaker in decibel (reference to maximum value) scale at 1000 Hz; every dimension of the measurement plane is normalized with wavelength.

5.3 Experimental results

Figure 12(a)-(c) shows the magnitude distribution of sound pressure after contrast control at each frequency. Since this is expressed in decibel scale when the reference is the maximum value, 0 dB means the maximum value of the sound pressure magnitude. Every dimension of the measurement plane is normalized by wavelength. Contrasts at selected frequencies are about 10.1 dB, 10.0 dB, and 10.2 dB, respectively. Different to the results of computer simulation, all the contrasts are about 10 dB. This shows consistent performance of the acoustic parasol at the selected frequencies. As the results of computer simulation, acoustic energy is focused symmetrically on the four regions at 800 Hz and 1000 Hz, and on the six regions at 1200 Hz. However, smaller size of the bright zone is generated at 800 Hz than in the case of the simulation, because we used loudspeakers for control sources which have directivity unlike the monopole source.



(a)



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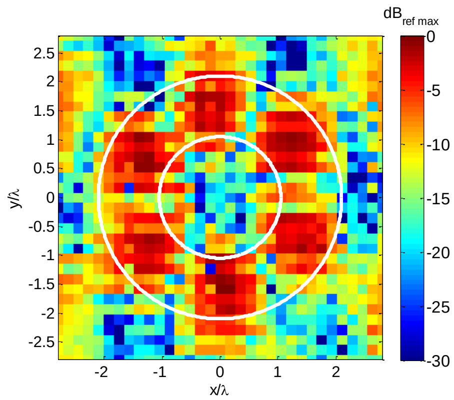

(c)

Figure 12. The pressure distribution after contrast control in decibel (reference to maximum value) scale in the selected frequencies; every dimension of the measurement plane is normalized with wavelength: (a) 800 Hz (b) 1000 Hz (c) 1200 Hz.

Figure 13 depicts the magnitude and phase of the optimized input signals of each loudspeaker after conatrast control at the selected frequencies. It is comparable to the optimum solutions in the case of computer simulation, loudspeakers positioned above bright zones have larger magnitude than loudspeakers positioned above the middle of the bright zones. In particular, the odd number of loudspeakers has larger magnitude than those of other loudspeakers at 1200 Hz. The magnitude and phase of the input signals is not symmetrically unlike the symmetric shape of the sound pressure distribution.

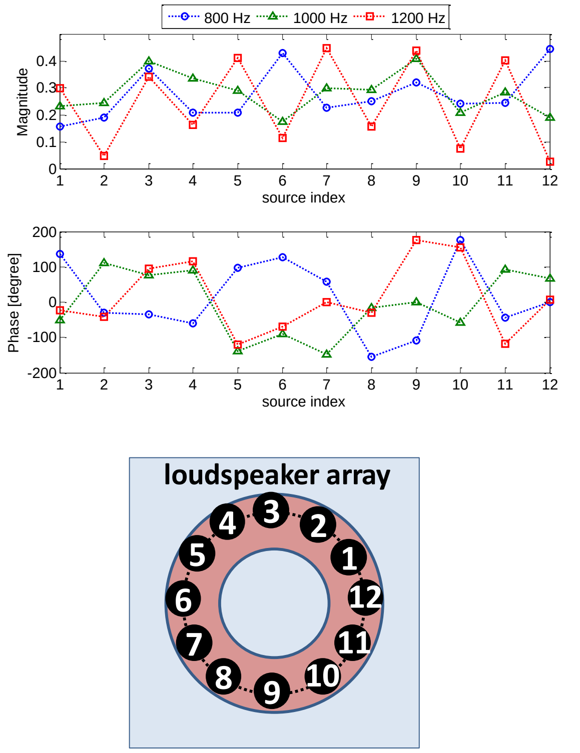

Figure 13. Magnitude and phase of the optimized input signals fed into each loudspeaker at selected frequencies: 800 Hz, 1000 Hz, and 1200 Hz

6. CONCLUSION

We carried out a feasibility study on applying contrast control to generate a private listening zone in a parasol. We enhanced acoustic energy at ring shaped bright zone where is around a table by using a circular loudspeaker array. In order to determine the loudspeaker arrangement which makes the maximum contrast by using the minimum number of loudspeaker, a computer simulation was done at selected frequencies: 800 Hz, 1000 Hz, and 1200 Hz. As a result of the simulation, we decided twelve loudspeakers and 0.5 m radius for the circular loudspeaker array in given conditions: 1.6 m × 1.6 m control zone 1 m away from the array speaker. At the selected frequencies, contrasts were 7.9 dB, 12.0 dB, and 11.3 dB, respectively. To verify this system with the determined parameters for loudspeaker arrangement, an experiment was carried out, and we compared the results with those of the computer simulation. As a result, all the contrasts were about 10 dB. Moreover, there was a similarity of the magnitude distribution of sound pressure between computer simulation and experiment.

In this study, contrast control was done only at narrow band frequencies, and scattering by users' head and a table was neglected. For application to real world, therefore, we need to accomplish further researches: contrast control in reverberant field, contrast control at wide band frequencies, and contrast control considering scatterers in control zone.

7. ACKNOWLEDGEMENTS

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