Robust time-domain acoustic contrast control design under uncertainties in the frequency response of the loudspeakers

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ABSTRACT

Time-domain acoustic contrast control method using loudspeaker array has been studied for generating bright and dark zones in personal audio system. Acoustic contrast which is defined as the acoustic energy ratio between bright and dark zones can be inevitably influenced by the uncertainties in the frequency response of loudspeakers. In this paper, a robust extension of broadband acoustic contrast control with response variation is proposed through exploiting knowledge of the statistical model of the uncertainties. Its performance is evaluated by Monte Carlo simulation method and compared with other acoustic contrast control methods. Simulation results show that better contrast over the continuous frequency range can be achieved using this proposed method.

Keywords: Acoustic contrast control, Robustness, Loudspeaker array I-INCE Classification of Subjects Number(s): 74.9

1. INTRODUCTION

Personal audio systems are used to generate acoustically bright and dark zones through loudspeaker array. It can provide a private listening space for users without disturbing other people. Among the optimization methods, acoustic contrast control (ACC) approach is more widely used for its simplicity and has attracted increasing interest in recent years (1). Its performance has been investigated in kinds of applications (2-7).

The performance of ACC approach can be degraded by the uncertainties in the frequency response of the loudspeakers (8). Shin et al. (9) used energy difference criterion instead of energy ratio to avoid the problem of matrix inversion. Elliott et al. (10) introduced array effort regularization to enhance the robustness performance against the uncertainties in the acoustic environment. Simón-Gálvez et al. (11) investigated the effects of reverberation in ordinary rooms. The simulation and experimental results show that the robustness of system performance can be improved similarly using the measured response in a reverberant environment as the array effort regularization approach. The robustness of ACC is improved from a different point of view in the paper (12). The uncertainties are assumed to have a certain probability distribution and be known in advance. These characteristics will be adopted in the design stage to reduce the sensitivity to uncertainties more effectively.

All the previous methods were designed in the frequency domain and we proposed a time-domain method recently, which is called broadband acoustic contrast control with response variation (BACC-RV) (13). Comparing with the ACC approach, a better acoustic contrast performance can be obtained over the whole frequency range. However, the robustness of BACC-RV is not well addressed. In this paper, a robust extension of BACC-RV method is presented where the probability distribution of the uncertainties in the frequency responses of loudspeakers is adopted. The rest of this paper is organized as follows: Section 2 states the problem and gives a short review of BACC-RV approach. The proposed robust extension of BACC-RV method is presented in Section 3.

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The simulation results and discussion are shown in Section 4. Finally, the conclusion is given in Section 5.

2. BACC-RV

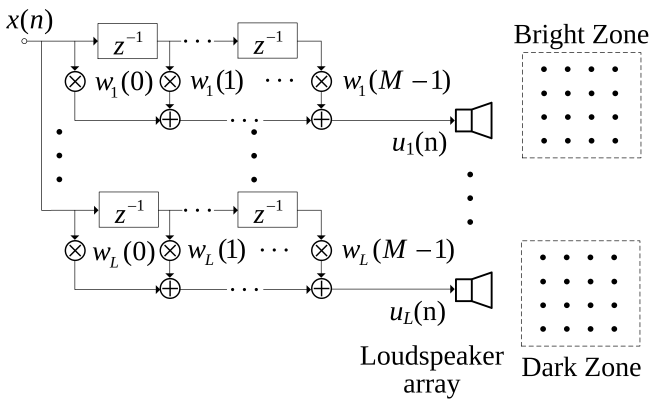


Figure 1 – The structure of BACC-RV

Figure 1 illustrates the structure of BACC-RV approach. Loudspeaker array is made up of L elements, and each loudspeaker is driven by the corresponding output of a finite impulse response (FIR) filter $w_l(n)$ with a length of M. The sampled output $y_{\mathrm{B}k}(n)$ at the kth control point in the bright zone can be written as

$$y_{\mathrm{B}k}(n) = \sum_{l=1}^{L}\sum_{i=0}^{I-1} h_{\mathrm{B}lk}(i)\sum_{m=0}^{M-1} w_l(m)x(n-m-i)\,, \tag{1}$$

where $h_{\mathrm{B}lk}(n)$ is the impulse response between the lth loudspeaker and kth control point in the bright zone, and its length is I. $x(n)$ is the input signal of the personal audio system.

Define the coefficient vector $\mathbf{w}$ and the filter signal vector $\mathbf{r}_{\mathrm{B}k}(n)$ as

$$\mathbf{w} = [w_1(0),\cdots,w_1(M-1),\cdots,w_L(0),\cdots,w_L(M-1)]^T\,, \tag{2}$$

and

$$\mathbf{r}_{\mathrm{B}k}(n) = [h_{\mathrm{B}1k}(n),\cdots,h_{\mathrm{B}1k}(n-M+1),\cdots,h_{\mathrm{B}Lk}(n),\cdots,h_{\mathrm{B}Lk}(n-M+1)]^T\,, \tag{3}$$

respectively. $[\square]^T$ is the transpose of the element. Assuming the input $x(n)$ is the Dirac delta function, the equation (1) can be expressed in vector form using equation (2) and (3) as

$$y_{\mathrm{B}k}(n) = \mathbf{w}^T\mathbf{r}_{\mathrm{B}k}(n)\,, \tag{4}$$

$y_{\mathrm{B}k}(n)$ is also the global impulse response with the length of $(M+I-1)$ in this case. As a result, the average acoustic energy e_{B} in the bright zone is

$$e_{\mathrm{B}} = \sum_{k=1}^{K}\sum_{n=0}^{M+I-2} y_{\mathrm{B}k}^2(n)/K = \mathbf{w}^T\mathbf{R}_{\mathrm{B}}\mathbf{w}\,, \tag{5}$$

where K is the number of control points in the bright zone and $\mathbf{R}_{\mathrm{B}} = \sum_{k=1}^{K}\sum_{n=0}^{M+I-2}\mathbf{r}_{\mathrm{B}k}(n)\mathbf{r}_{\mathrm{B}k}^T(n)/K$ is defined as the normalized correlation matrix in the bright zone.

The frequency response $p_{\mathrm{B}k}(\omega)$ in the bright zone is

$$p_{\mathrm{B}k}(\omega) = \sum_{n=0}^{M+I-2} y_{\mathrm{B}k}(n)e^{-j\omega n} = \mathbf{w}^T\mathbf{s}_{\mathrm{B}k}(\omega)\,, \tag{6}$$

where ω is the digital angular frequency. $\mathbf{s}_{\mathrm{B}k}(\omega)$ is the vector given as

$$\mathbf{s}_{\mathrm{B}k}(f) = [\mathbf{r}_{\mathrm{B}k}(0),\cdots,\mathbf{r}_{\mathrm{B}k}(M+I-2)][1,e^{-j\omega},\cdots,e^{-j\omega(I+M-2)}]^T\,, \tag{7}$$

Response variation (RV) term (13) measures the variation of response over the frequency range of interest in the bright zone and it can be formulated as

$$\mathrm{RV} = \frac{1}{JK}\sum_{k=1}^{K}\sum_{j=1}^{J}\left|p_{\mathrm{B}k}(\omega_j) - p_{\mathrm{B}k}(\omega_{\mathrm{ref}})\right|^2, \tag{8}$$

where ω_{ref} is the reference angular frequency and J is the number of frequency bins. In order to achieve good contrast over the frequency range and get flat frequency response, BACC-RV approach leads to the following optimization problem:

$$\max_{\mathbf{w}} \quad \frac{\mathbf{w}^T\mathbf{R}_\mathrm{B}\mathbf{w}}{\beta\mathbf{w}^T\mathbf{R}_\mathrm{D}\mathbf{w} + (1-\beta)\mathrm{RV} + \delta\mathbf{w}^T\mathbf{w}}, \tag{9}$$

where $\mathbf{R}_\mathrm{D}$ is the normalized correlation matrix in the dark zone. β is a weight factor with the value between 0 and 1. δ is a regularization parameter.

3. ROBUST EXTENTION OF BACC-RV

Although BACC-RV has a regularization term, it does not directly take into account the uncertainties in the frequency responses of loudspeakers. The frequency response of each loudspeaker is assumed to be unrealistic consistency. The effect of uncertainties in frequency response of the lth loudspeaker is modeled as

$$A_l(\omega) = a_l(\omega)e^{-j\phi_l(\omega)}, \tag{10}$$

where $a_l(\omega)$ and $\phi_l(\omega)$ is gain and phase respectively. Therefore the frequency response $\overline{p}_{\mathrm{B}k}(\omega)$ under uncertainties is

$$\overline{p}_{\mathrm{B}k}(\omega) = \mathbf{w}^T[\mathbf{s}_{\mathrm{B}k}(\omega)\circ\mathbf{A}], \tag{11}$$

where $\circ$ is hadamard product. $\mathbf{A}$ is the $ML\times 1$ vector

$$\mathbf{A} = [\underbrace{A_1(\omega),\cdots,A_1(\omega)}_{M\times 1},\cdots,\underbrace{A_L(\omega),\cdots,A_L(\omega)}_{M\times 1}]^T, \tag{12}$$

Using Parceval's theorem, the average acoustic energy $\overline{e}_\mathrm{B}$ in the bright zone is

$$\overline{e}_\mathrm{B} = \sum_{k=1}^{K}\frac{1}{2\pi}\int_{-\pi}^{\pi}\left|\overline{p}_{\mathrm{B}k}(\omega)\right|^2 d\omega / K, \tag{13}$$

Because $\overline{e}_\mathrm{B}$ is random variable, we only consider the mean value of $\overline{e}_\mathrm{B}$. As a result,

$$\begin{aligned}\mathrm{E}\{\overline{e}_\mathrm{B}\} &= \mathbf{w}^T\mathrm{E}\{\sum_{k=1}^{K}\frac{1}{2\pi}\int_{-\pi}^{\pi}[\mathbf{s}_{\mathrm{B}k}(\omega)\circ\mathbf{A}]^H[\mathbf{s}_{\mathrm{B}k}(\omega)\circ\mathbf{A}]d\omega/K\}\mathbf{w} \\ &= \mathbf{w}^T\sum_{k=1}^{K}\frac{1}{2\pi}\int_{-\pi}^{\pi}\mathbf{s}_{\mathrm{B}k}(\omega)^H\mathbf{s}_{\mathrm{B}k}(\omega)\circ\mathrm{E}\{\mathbf{A}^H\mathbf{A}\}d\omega/K\mathbf{w}\end{aligned}, \tag{14}$$

where $\mathrm{E}\{\cdot\}$ stands for expectation. Assuming that all of the uncertainties variables $a_l(\omega)$ and $\phi_l(\omega)$ are independent. All of the probability density functions of the $a_l(\omega)$ and $\phi_l(\omega)$ are the same, respectively. Therefore

$$\begin{aligned}&\mathrm{E}\{\mathbf{A}^H\mathbf{A}\} = (\sigma_a^2 - \mu_a^2\sigma_\gamma^c)\mathrm{diag}(\mathbf{1}_{ML\times 1}) + \mu_a^2\sigma_\gamma^c\mathbf{1}_{ML\times ML} \\ &\sigma_a^2 = \mathrm{E}\{a^2\}, \quad \mu_a = \mathrm{E}\{a\} \\ &\sigma_\gamma^c = [\mathrm{E}\{\cos\phi\}]^2 + [\mathrm{E}\{\sin\phi\}]^2\end{aligned}, \tag{15}$$

where $\mathrm{diag}(\mathbf{v})$ represents the matrix whose main diagonal is the vector $\mathbf{v}$, and $\mathbf{1}_{m\times n}$ is the $m\times n$ matrix whose elements are all one.

It can be seen from Eq. (15) that $\mathrm{E}\{\mathbf{A}^H\mathbf{A}\}$ is a constant matrix and independent of ω. Therefore, using Eq. (5) and defining $\Delta\mathbf{R} = \mathrm{E}\{\mathbf{A}^H\mathbf{A}\}$, Eq. (14) can be formatted as

$$\mathrm{E}\{\overline{e}_\mathrm{B}\} = \mathbf{w}^T(\mathbf{R}_\mathrm{B}\circ\Delta\mathbf{R})\mathbf{w}, \tag{16}$$

As a result, the robust extension of BACC-RV can be written as

$$\max_{\mathbf{w}} \quad \frac{\mathbf{w}^T(\mathbf{R}_\mathrm{B}\circ\Delta\mathbf{R})\mathbf{w}}{\beta\mathbf{w}^T(\mathbf{R}_\mathrm{D}\circ\Delta\mathbf{R})\mathbf{w} + (1-\beta)\mathrm{RV}}, \tag{17}$$

It can be learned from Eq. (17) that robust extension of BACC-RV exploited the knowledge of the statistical model of the uncertainties.

4. SIMULATION

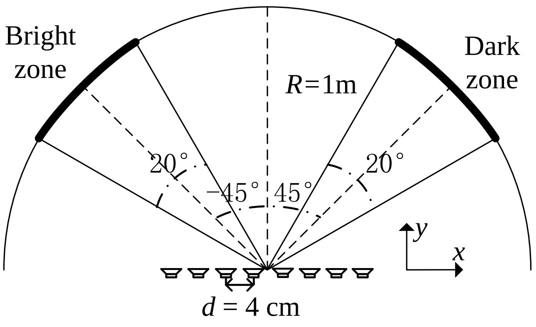


Figure 2 – The simulation set-up

The simulation set-up is illustrated in Figure 2. The loudspeaker array consists of eight loudspeaker units with a spacing d of 4 cm, which is about half wavelength of 4 kHz. The bright zone and dark zone are located at the −45 ° and 45 ° direction deviated from the center of loudspeaker array respectively. The radius R is 1 m. The range of each zone is 20 ° and its size is about 35 cm, which is enough for head size and its movement. Each zone is represented by twenty one control points with spacing of 1 °.

The frequency range of interest is selected from 200 Hz to 3800 Hz, which covers the frequency range of speech. The impulse response between the loudspeaker array and control points is generated by the RIR toolbox(14). The length I of the impulse response is set to be 1600 and its sampling frequency is 8000 Hz. Therefore, the time length of impulse response is 0.2 s, which is long enough for free field condition.

The probability distribution of uncertainties is simulated using uniform and normal distribution respectively. In uniform distribution, the gain a is distributed uniformly in interval [0.88, 1.12], the phase ϕ is distributed uniformly in interval [−24 °, 24 °]。 In normal distribution, the mean and standard deviation value of gain a is 1 and 0.04, the mean and standard deviation value of phase ϕ is 0 ° and 8 °.

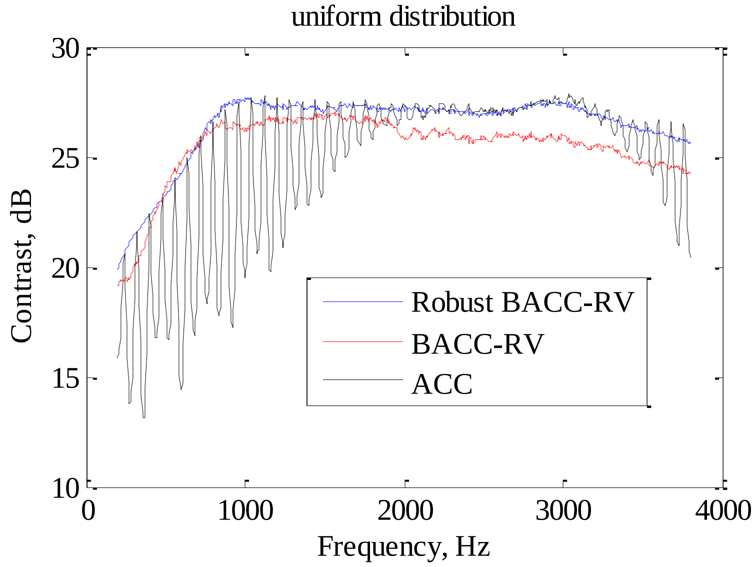
ACC, BACC-RV and robust extension of BACC-RV approaches are investigated in this paper. ACC approach also use the knowledge of the statistical model of the uncertainties and its computation can be found in reference (12). The weight factor β and regularization parameter δ in BACC-RV method is 0.5 and 0.000005 respectively. The weight factor β in robust extension of BACC-RV method is 0.5. The reference frequency is 2 kHz. The length M of filter is set to be 100. Thus, the control frequency interval for ACC method is 80 Hz.

The performance of these methods are evaluated by mean value of acoustic contrast in the frequency domain

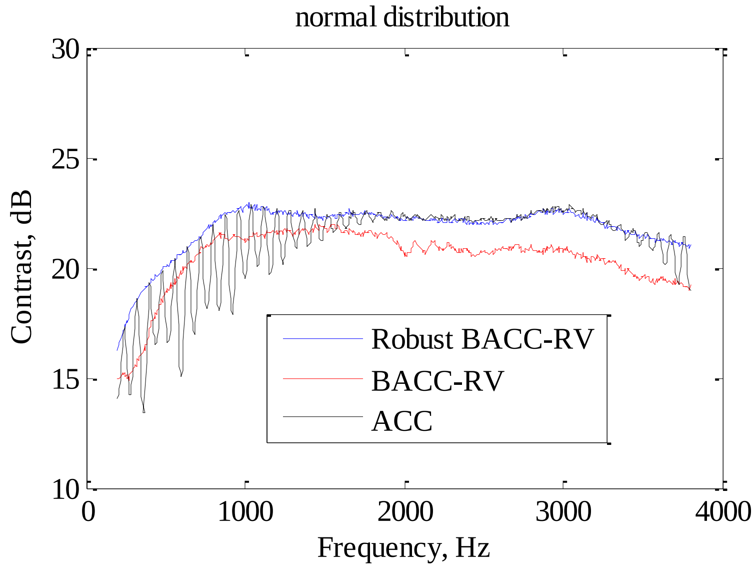
$$C_f = \mathrm{E}\left\{ \frac{1}{K} \sum_{k=1}^{K} \left| \overline{p}_{\mathrm{B}k}(f) \right|^2 / \frac{1}{K_d} \sum_{k=1}^{K_D} \left| \overline{p}_{\mathrm{D}k}(f) \right|^2 \right\}, \tag{18}$$

where $\left|\overline{p}_{\mathrm{D}k}(f)\right|$ is the is the frequency response considering uncertainties at the kth control point in the dark zone, and K_{D} is the number of control points. Eq. (18) is computed by Monte Carlo simulation method (15), where five thousand random samples are obtained.

Figure 3 illustrates the mean value of contrast against frequency with different approaches mentioned above. The investigated frequency interval is 5 Hz. It can be seen from Fig. 3 that ACC method can only achieve good contrast at control frequencies. BACC-RV can obtain good contrast over the frequency range of interest. Using the knowledge of the statistical model of the uncertainties, robust extension of BACC-RV can achieve better contrast over all the frequency ranges, compared with BACC-RV method. At the frequency larger than 2 kHz, the contrast by robust extension of BACC-RV approach is about 2 dB larger than that by BACC-RV method.



(a)



(b)

Figure 3 –The mean value of contrast against frequency under different distributions of the uncertainties in the frequency response of the loudspeaker, (a) uniform distribution, the gain a is distributed uniformly in interval [0.88, 1.12], the phase ϕ is distributed uniformly in interval [−24°, 24°], (b) normal distribution, the mean and standard deviation value of gain a is 1 and 0.04, the mean and standard deviation value of phase ϕ is 0° and 8°

5. CONCLUSIONS

A method using the knowledge of the statistical model of the uncertainties in the frequency response of the loudspeakers is proposed to generate bright and dark zones over the continuous frequency range in personal audio system. It is a robust improved version of our previous proposed method BACC-RV. Computer simulations demonstrate the effectiveness of the proposed method under uniform and normal distributions of the uncertainties in the frequency of loudspeaker. Compared with BACC-RV approach, the average contrast with a value of more than 2 dB at the frequency larger than 2 kHz can be improved by this presented method.

ACKNOWLEDGEMENTS

This work was supported by National Natural Science Fund of China under Grants Nos. 11174317, and 11304349.

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