CAR CABIN PERSONAL AUDIO: ACOUSTIC CONTRAST WITH LIMITED SOUND DIFFERENCES

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The generation of independent or personal listening zones is of significant interest in the car cabin environment. As such there are a number of methods of optimizing loudspeaker arrays to achieve personal audio reproduction. The optimization methods currently in the literature generally have a trade-off between the level of acoustic contrast between the bright and dark zones and the variance of the sound pressure within the bright zone. A high level of variance in the bright zone may produce a subjectively poor performance and although this may be overcome using the least squares or acoustic contrast with planarity control methods, they are generally non-trivial to setup to achieve both a high level of acoustic contrast and a low level of variance. This paper proposes a new optimization method which maximizes the acoustic contrast with a constraint that limits the sound differences within the bright zone and is relatively straightforward to setup. The performance of the proposed optimization method is compared to acoustic contrast maximization, least squares and acoustic contrast maximization with planarity control methods through a series of simulations of a car cabin personal audio system.

1 INTRODUCTION

A car cabin is probably one of the most frequently used acoustic environments for sound reproduction. The evidence is shown in the latest high end car audio systems which may have a 5.1 channel surround sound system with 15 speakers or a 7.1 channel surround sound system with 17 speakers for example [1]. However, these sound systems are designed assuming that all passengers hear the same sound, despite the different passenger's needs. For example, one passenger may require entertainment sound, like the radio or music, while the driver often requires a quiet environment in order to concentrate on driving and to be able to hear announcements from the car navigation system. Therefore, a method of optimizing a personal audio system to provide different sound zones in a car cabin using a loudspeaker array is studied in this paper.

Current methods for optimizing personal audio systems tend to result in a trade-off between a large variance in the sound pressure within the control zones and the achieved level of acoustic contrast. For example, Acoustic Contrast optimization enables a given loudspeaker array to achieve the highest acoustic contrast, but it shows a high variance of sound energy [2]. On the other hand, Least-Squares optimization, which requires the definition of a target pressure field, produces a low sound energy variance, but the acoustic contrast level tends to be limited [3]. Recently, Planarity optimization was presented [4] to deal with these problems. However, this method is not trivial to setup as it requires a number of parameters to be defined. This paper proposes a new optimization method to limit the differences in the sound field within the listening zone whilst maximizing the acoustic contrast between the bright zone and the dark zone.

In order to test the proposed optimization method and compare its performance to the previously proposed optimization methods, we represent a car cabin as a rectangular room with dimensions of 3m×1.8m×1.3m as shown in Fig.1. In this instance two control zones are defined as the front zone and rear zone, which are shown in Fig. 1 and Tab. 1. Each zone is defined by a three-dimensional grid of 135 microphones. The personal audio system attempts to produce two independent listening zones, as in [5].

As shown in [5], at low frequencies it is possible to produce independent listening zones for the geometry presented in Fig. 1 using the four standard car audio loudspeakers. These are generally fitted to the lower part of car doors and their positions in this case are shown by the red circles in Fig. 1.

To achieve independent listening zones at higher frequencies it is not possible to use the standard low frequency car audio loudspeakers because the acoustical modes are dense [5]. Therefore, to achieve control at higher frequencies an array of 16 headrest loudspeakers located close to the positions of the occupants' heads is introduced. This is an extension compared to the work presented in [5], where 8 directional loudspeakers are positioned at the headrest locations. The positions of the headrest loudspeakers are shown in Fig. 1 by the red points and in Tab. 3.

Section 2 initially presents a review of three methods of optimizing personal audio systems that are available within the literature, namely the Acoustic Contrast (AC) maximization method, the Least-Squares (LS) method and the Acoustic Contrast with Planarity Control (ACP) method. A new method of optimization is then presented, which is based on limiting the sound differences within the bright zone. In Section 3 the performance of the four optimization methods is compared in the context of the car cabin personal audio problem. Finally, Section 4 presents the conclusions.

Table1 Bright and dark zone sampling distance 0.1 m

Zone name	x [m]	y [m]	z [m]
Front zone	1.0 to 1.2	0.2 to 1.6	0.8 to 1.0
Rear zone	2.0 to 2.2	0.2 to 1.6	0.8 to 1.0

Table2 Audio array speaker locations

Speaker number	x [m]	y [m]	z [m]
1	0.75	0	0.3
2	0.75	1.8	0.3
3	1.75	0	0.4
4	1.75	1.8	0.4

Table3 Headrest speakers

Speaker number	x [m]	y [m]	z [m]
1, 2	1.3∓0.02	0.3	0.9
3, 4	1.3∓0.02	0.5	0.9
5, 6	1.3∓0.02	1.3	0.9
7, 8	1.3∓0.02	1.5	0.9
9, 10	2.3∓0.02	0.3	0.9
11, 12	2.3∓0.02	0.5	0.9
13, 14	2.3∓0.02	1.3	0.9
15, 16	2.3∓0.02	1.5	0.9

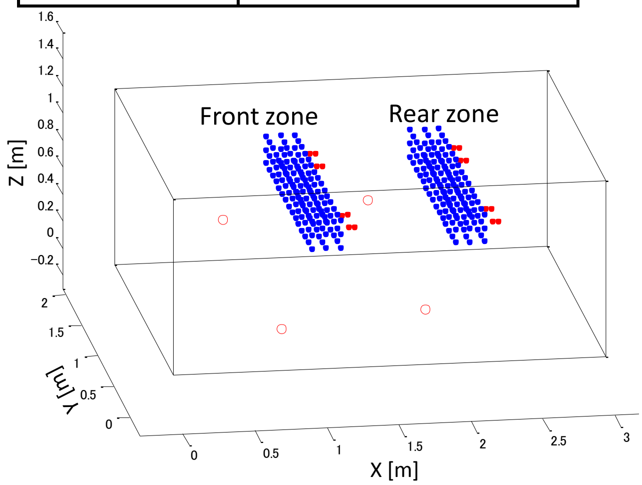


Figure 1: Controlled zones in car cabin (blue points), original car audio array (red circles) and headrest speaker array (red points).

2 THEORY

To produce independent listening zones we define two zones: the bright zone, where the sound is focused, and the dark zone, in which the sound pressure level is kept low. To evaluate the performance of the optimized personal audio system we first define three performance metrics. To evaluate the ability of the system to produce a difference in the sound pressure levels between the two zones, we define the acoustic contrast as the ratio of the averaged sound pressure levels in each zone:

$$Acoustic\ Contrast = \frac{\mathrm{L_D} \boldsymbol{p_B}^{\mathrm{H}} \boldsymbol{p_B}}{\mathrm{L_B} \boldsymbol{p_D}^{\mathrm{H}} \boldsymbol{p_D}} = \frac{\mathrm{L_D} \boldsymbol{q}^{\mathrm{H}} \boldsymbol{Z_B}^{\mathrm{H}} \boldsymbol{Z_B} \boldsymbol{q}}{\mathrm{L_B} \boldsymbol{q}^{\mathrm{H}} \boldsymbol{Z_D}^{\mathrm{H}} \boldsymbol{Z_D} \boldsymbol{q}} \quad (1)$$

where $\boldsymbol{p_B}$ and $\boldsymbol{p_D}$ are the vectors of complex sound pressures at $\mathrm{L_B}$ discrete points in the bright and $\mathrm{L_D}$ discrete points in the dark zone respectively, $\boldsymbol{q}$ is the complex input to the M loudspeakers and $\boldsymbol{Z_B}$ and $\boldsymbol{Z_D}$ are the matrices of transfer responses, which are $(L_B \times M)$ and $(L_D \times M)$ in size respectively.

To evaluate the electrical power required by the optimized loudspeaker array we define the array effort as

$$Array\ Effort = \frac{\boldsymbol{q}^{\mathrm{H}} \boldsymbol{q}}{\boldsymbol{q_r}^{\mathrm{H}} \boldsymbol{q_r}} \quad (2)$$

where $\boldsymbol{q_r}$ is the vector of input signals required to produce the same bright zone pressure when the loudspeakers are driven in-phase.

To assess the variation in the sound field within the bright zone, we define the standard deviation as

$$\sigma = \left(\frac{1}{\mathrm{L_B}} \sum_{n=1}^{\mathrm{L_B}} \left(10\log_{10} \frac{\{\boldsymbol{p}\}_n^{*} \{\boldsymbol{p}\}_n}{\mathrm{p_{ave}}^{*} \mathrm{p_{ave}}} \right)^2 \right)^{1/2} \quad (3)$$

where $\mathrm{p_{ave}}$ is the average sound pressure and $\{\boldsymbol{p}\}_n$ is the nth vector element of $\boldsymbol{p}$.

2.1 Acoustic Contrast Optimization

AC (Acoustic Contrast optimization) [2] maximizes the difference between the sum of the squared pressures in the bright zone and the dark zone. The cost function is written as

$$J_{AC} = \boldsymbol{q}^{\mathrm{H}} \boldsymbol{Z_D}^{\mathrm{H}} \boldsymbol{Z_D} \boldsymbol{q} + \lambda_C \left(\boldsymbol{q}^{\mathrm{H}} \boldsymbol{Z_B}^{\mathrm{H}} \boldsymbol{Z_B} \boldsymbol{q} - B \right) + \lambda_M \left(\boldsymbol{q}^{\mathrm{H}} \boldsymbol{q} - \mathrm{E_m} \right). \quad (4)$$

where B is a constraint on the sum of the squared pressures in the bright zone, $\mathrm{E_m}$ is a constraint on the electrical power required by the array, and both λ_C and λ_M are Lagrange multipliers. According to this cost function, the optimal $\boldsymbol{q}$ is given by the eigenvalue problem

$$\lambda_C \boldsymbol{q} = \left(\boldsymbol{Z_B}^{\mathrm{H}} \boldsymbol{Z_B} \right)^{-1} \left(\boldsymbol{Z_D}^{\mathrm{H}} \boldsymbol{Z_D} + \lambda_M \boldsymbol{I} \right) \boldsymbol{q}. \quad (5)$$

The optimal loudspeaker driving signal vector is proportional to the eigenvector corresponding to the smallest eigenvalue of $(\boldsymbol{Z_B}^{\mathrm{H}}\boldsymbol{Z_B})^{-1}(\boldsymbol{Z_D}^{\mathrm{H}}\boldsymbol{Z_D}+\lambda_{\mathrm{M}})$.

2.2 Least-Squares Optimization

LS (Least-Squares optimization) [3] minimizes the error defined by the differences between the target pressure, which must be defined, and the pressure produced by the loudspeaker array. The error vector is defined as

$$\boldsymbol{e} = \boldsymbol{p_T} - \boldsymbol{p} \tag{6}$$

where $\boldsymbol{p_T}$ is the vector of target pressures, and the cost function is expressed as

$$J_{LS} = \mathbf{e}^{\mathrm{H}}\boldsymbol{e} + \lambda_M(\boldsymbol{q}^{\mathrm{H}}\boldsymbol{q} - \mathrm{E_m}). \tag{7}$$

Differentiating equation 7 with respect to $\boldsymbol{q}$ gives,

$$\frac{\partial J_{LS}}{\partial \boldsymbol{q}} = -\boldsymbol{Z}^{\mathrm{H}}(\boldsymbol{p_T} - \boldsymbol{Z}\boldsymbol{q}) + \lambda_M \boldsymbol{q} \tag{8}$$

equating this to zero and rearranging gives the optimal input signal vector as

$$\boldsymbol{q} = (\boldsymbol{Z}^{\mathrm{H}}\boldsymbol{Z} + \lambda_M \boldsymbol{I})^{-1}\boldsymbol{Z}^{\mathrm{H}}\boldsymbol{p_T}\,. \tag{9}$$

where for the personal audio problem the matrix of transfer responses is defined as

$$\boldsymbol{Z} = \begin{bmatrix}\boldsymbol{Z_B}\\ \boldsymbol{Z_D}\end{bmatrix}. \tag{10}$$

2.3 Acoustic Contrast with Planarity Optimization

ACP (Acoustic Contrast with Planarity) [4] attempts to produce a more planar sound field than the other control optimization methods. The cost function is given by

$$J_{ACP} = \boldsymbol{q}^{\mathrm{H}}\boldsymbol{Z_D}^{\mathrm{H}}\boldsymbol{Z_D}\boldsymbol{q} + \lambda_C\left(\boldsymbol{q}^{\mathrm{H}}\boldsymbol{Z_B}^{\mathrm{H}}\boldsymbol{H_B}^{\mathrm{H}}\boldsymbol{\Gamma}\boldsymbol{H_B}\boldsymbol{Z_B}\boldsymbol{q} - B\right) + \lambda_M(\boldsymbol{q}^{\mathrm{H}}\boldsymbol{q} - \mathrm{E_m}), \tag{11}$$

where $\boldsymbol{H_B}$ is a steering matrix for the bright zone and $\boldsymbol{\Gamma}$ is a weighting matrix which defines the acceptable range of angles for incoming plane waves to the bright zone. The optimal solution is given by

$$\lambda_C \boldsymbol{q} = \left(\boldsymbol{Z_B}^{\mathrm{H}}\boldsymbol{H_B}^{\mathrm{H}}\boldsymbol{\Gamma}\boldsymbol{H_B}\boldsymbol{Z_B}\right)^{-1}\left(\boldsymbol{Z_D}^{\mathrm{H}}\boldsymbol{Z_D} + \lambda_M \boldsymbol{I}\right)\boldsymbol{q}. \tag{12}$$

The optimal input signals are given in this case by the eigenvector corresponding to the smallest eigenvalue of

$$\left(\boldsymbol{Z_B}^{\mathrm{H}}\boldsymbol{H_B}^{\mathrm{H}}\boldsymbol{\Gamma}\boldsymbol{H_B}\boldsymbol{Z_B}\right)^{-1}\left(\boldsymbol{Z_D}^{\mathrm{H}}\boldsymbol{Z_D} + \lambda_M\right). \tag{13}$$

The steering matrix can be written as

$$\boldsymbol{H_B} = \begin{pmatrix}\boldsymbol{h_1}\\ \vdots \\ \boldsymbol{h_i} \\ \vdots \\ \boldsymbol{h_{LB}}\end{pmatrix} \tag{14}$$

where $\boldsymbol{h_i}$ is a column vector corresponding to the maximum eigenvalue of

$$\left(\boldsymbol{S_i}^{\mathrm{H}}\boldsymbol{S_i} + \beta \boldsymbol{I}\right)^{-1}\boldsymbol{P_i}^{\mathrm{H}}\boldsymbol{P_i} \tag{15}$$

where $\boldsymbol{P_i}$ and $\boldsymbol{S_i}$ are the pass band and stop band, which is expressed as

$$\boldsymbol{P_i} = \{g_{p,c}\},\ \ \boldsymbol{S_i} = \{g_{s,c}\}. \tag{16}$$

$\mathrm{g_{i,c}}$ is plane wave Green's function with band range i which is expressed as

$$\mathrm{g_{i,c}} = \frac{\boldsymbol{e}^{\mathrm{j}k r_c \boldsymbol{u_i}}}{\mathrm{L}_B}\ ,\boldsymbol{u_i} = \begin{pmatrix} sin\varphi \\ cos\varphi \end{pmatrix} \tag{17}$$

where subscripts p, s and c denote passband range, stopband range and look direction between center of the bright zone and component of plane wave respectively. In the following simulations, β which is the regularization parameter is 10^{-4}, and the passband range and stopband range are 1 and 2 degrees respectively.

2.4 Acoustic Contrast with Limited Sound Differences

The optimization methods outlined above have focused on maximizing the acoustic contrast, minimizing the differences between the target sound pressures and the reproduced sound pressures, and constraining the incoming angle of sound into the bright zone. Although the AC method may achieve a large acoustic contrast between the bright and dark zones, it does not constrain the variation in the pressure within the bright zone and this may produce subjectively poor results. This problem is addressed in the LS method by defining a target sound field; however, it may be somewhat difficult to define this to achieve both subjectively pleasing results and a high level of acoustic contrast. The ACP method attempts to overcome this limitation by placing a constraint on the range of angles over which reproduced plane waves can enter the bright zone. However, this method is not straightforward and still requires a number of parameters to be defined in advance. Therefore, we consider an optimization method in which the acoustic contrast is maximized, whilst the variance in the sound pressure within the bright zone is constrained. This constraint can be achieved based on limiting the differences between the sound pressure levels at all points within the bright zone which can be written as

$$\sum_{\mathrm{n}=1}^{\mathrm{L_B}-1}(\boldsymbol{p_B} - \boldsymbol{p_{B-n}})^{\mathrm{H}}(\boldsymbol{p_B} - \boldsymbol{p_{B-n}}), \tag{18}$$

where $\boldsymbol{p_{B-n}}$ is a shifted vector of the pressure in the bright zone, so that the summation includes the squared difference between each point in the bright zone and every other point in the bright zone. Therefore, the method is termed acoustic contrast maximization with limited sound pressure differences (ACLD). The cost function for this method is given by

$$J_{ACLD} = \boldsymbol{q}^{\mathrm{H}}\boldsymbol{Z_D}^{\mathrm{H}}\boldsymbol{Z_D}\boldsymbol{q} + \lambda_C\left(\boldsymbol{q}^{\mathrm{H}}\boldsymbol{Z_B}^{\mathrm{H}}\boldsymbol{Z_B}\boldsymbol{q} - B\right) + \lambda_M(\boldsymbol{q}^{\mathrm{H}}\boldsymbol{q} - \mathrm{E_m}) + \lambda_{LD}\sum_{\mathrm{n}=1}^{\mathrm{L_B}-1}\boldsymbol{q}^{\mathrm{H}}(\boldsymbol{Z_B}^{\mathrm{H}} - \boldsymbol{Z_{B-n}}^{\mathrm{H}})(\boldsymbol{Z_B} - \boldsymbol{Z_{B-n}})\boldsymbol{q}\,, \tag{19}$$

$$\text{if } \mathrm{i} \geq \mathrm{n}+1 \qquad \{\boldsymbol{Z_{B-n}}\}_{\boldsymbol{i,j}} = \{\boldsymbol{Z_B}\}_{\boldsymbol{i+n-1,j}}$$

$$\text{if } \mathrm{i} \leq \mathrm{n} \qquad \{\boldsymbol{Z_{B-n}}\}_{\boldsymbol{i,j}} = \{\boldsymbol{Z_B}\}_{\boldsymbol{i}+\mathrm{L_B}-\boldsymbol{n,j}}$$

which are matrices of shifted impedances, where λ_{LD} is a Lagrange multiplier which defines the limit on the sound differences within the bright zone and can thus be varied to trade-off between acoustic contrast performance and the uniformity of the sound field in the bright zone. i and j are the ith row and jth column of the transfer response matrix. The last part of equation 19 can be expanded as

$$\boldsymbol{q}^{\mathrm{H}}\left(\boldsymbol{Z_B}^{\mathrm{H}}-\boldsymbol{Z_{B-n}}^{\mathrm{H}}\right)(\boldsymbol{Z_B}-\boldsymbol{Z_{B-n}})\boldsymbol{q} = \begin{pmatrix} \mathrm{p}_{\mathrm{B}_1}-\mathrm{p}_{\mathrm{B}_{\mathrm{L_B}-n+1}} \\ \vdots \\ \mathrm{p}_{\mathrm{B}_{n-1}}-\mathrm{p}_{\mathrm{B}_{\mathrm{L_B}-1}} \\ \mathrm{p}_{\mathrm{B}_n}-\mathrm{p}_{\mathrm{B}_{\mathrm{L_B}}} \\ \mathrm{p}_{\mathrm{B}_{n+1}}-\mathrm{p}_{\mathrm{B}_1} \\ \vdots \\ \mathrm{p}_{\mathrm{B}_{\mathrm{L_B}}}-\mathrm{p}_{\mathrm{B}_{\mathrm{L_B}-n}} \end{pmatrix}^{\mathrm{H}} \begin{pmatrix} \mathrm{p}_{\mathrm{B}_1}-\mathrm{p}_{\mathrm{B}_{\mathrm{L_B}-n+1}} \\ \vdots \\ \mathrm{p}_{\mathrm{B}_{n-1}}-\mathrm{p}_{\mathrm{B}_{\mathrm{L_B}-1}} \\ \mathrm{p}_{\mathrm{B}_n}-\mathrm{p}_{\mathrm{B}_{\mathrm{L_B}}} \\ \mathrm{p}_{\mathrm{B}_{n+1}}-\mathrm{p}_{\mathrm{B}_1} \\ \vdots \\ \mathrm{p}_{\mathrm{B}_{\mathrm{L_B}}}-\mathrm{p}_{\mathrm{B}_{\mathrm{L_B}-n}} \end{pmatrix}. \quad (20)$$

Differentiating equation 19 gives

$$\frac{\partial J_{ACLD}}{\partial \boldsymbol{q}} = \boldsymbol{Z_D}^{\mathrm{H}}\boldsymbol{Z_D}\boldsymbol{q} + \lambda_C \boldsymbol{Z_B}^{\mathrm{H}}\boldsymbol{Z_B}\boldsymbol{q} + \lambda_M \boldsymbol{q} + \lambda_{LD}\boldsymbol{\Xi}\boldsymbol{q}, \quad (21)$$

where

$$\boldsymbol{\Xi} = (\mathrm{L_B}-1)\boldsymbol{Z_B}^{\mathrm{H}}\boldsymbol{Z_B} + \sum_{n=1}^{\mathrm{L_B}-1}\left(\boldsymbol{Z_{B-n}}^{\mathrm{H}}\boldsymbol{Z_{B-n}} - \boldsymbol{Z_B}^{\mathrm{H}}\boldsymbol{Z_{B-n}} - \boldsymbol{Z_{B-n}}^{\mathrm{H}}\boldsymbol{Z_B}\right). \quad (22)$$

The optimal signal vector in this case is proportional to the eigenvector corresponding to the smallest eigenvalue of

$$\left(\boldsymbol{Z_B}^{\mathrm{H}}\boldsymbol{Z_B}\right)^{-1}\left(\boldsymbol{Z_D}^{\mathrm{H}}\boldsymbol{Z_D} + \lambda_M \boldsymbol{I} + \lambda_{LD}\boldsymbol{\Xi}\right). \quad (23)$$

3 SIMULATION

3.1 Car audio array

The car audio array loudspeakers are modelled as monopoles in the following simulations and the enclosure is modelled using a modal model [5]. The modal model includes the contribution from 4420 acoustic modes with natural frequencies up to 1.8 kHz and a damping ratio of 0.1. For the LS method,

$$\boldsymbol{p_T} = \begin{bmatrix} \boldsymbol{p_{T\_B}} \\ \boldsymbol{p_{T\_D}} \end{bmatrix}, \begin{cases} \boldsymbol{p_{T\_B}} = \boldsymbol{Z_B}\vec{\mathbf{1}} \\ \boldsymbol{p_{T\_D}} = \vec{\mathbf{0}} \end{cases}, \vec{\mathbf{0}} = \begin{pmatrix} \mathbf{0} \\ \vdots \\ \mathbf{0} \end{pmatrix}, \vec{\mathbf{1}} = \begin{pmatrix} \mathbf{1} \\ \vdots \\ \mathbf{1} \end{pmatrix} \quad (24)$$

which means that the target pressures in the bright zone are the pressures produced when the four car audio array loudspeakers are driven in-phase and the pressures in the dark zone are zero.

For the ACLD method the Lagrange multiplier which governs the constraint on the limited sound differences, λ_{LD}, has been defined to ensure that the standard deviation is less than 10.4 dB at each frequency.

3.1.1 Acoustic contrast and array effort

Figure 2 shows the acoustic contrast and array effort for the three previously proposed optimization methods and the new ACLD method. From these results it can be seen that AC achieves the highest contrast value, followed by ACLD, LS and finally ACP. At higher frequencies, the acoustic contrast achieved by all four optimization methods is limited because the acoustical modes are very dense.

With regard to the array effort required to produce the front bright zone, ACLD, LS and ACP are lower than the AC optimization method over the frequency range where the array can achieve a significant acoustic contrast. The AC method has the highest array effort because of the higher acoustic contrast that it achieves. When producing a rear bright zone, the array effort is around the same level for all of the optimization methods, since they all achieve a similar level of acoustic contrast.

3.1.2 Standard deviation of sound pressure and sound distribution

Although acoustic contrast is one of the most important factors for assessing the performance of a personal audio system, the standard deviation of the sound pressures in the bright zone provides an indication of the spatial variation in the sound pressure. This is important since when a passenger in the bright zone moves a small distance, if the standard deviation of the sound pressure is high then they are likely to hear a large difference in sound pressure level despite staying in the bright zone. Figure 3 shows the standard deviation of the sound pressure levels in the bright zone as defined in equation (3) for the four optimization strategies. From the results presented in the upper plot of Fig. 3 it can be seen that for a front bright zone the standard deviation is very low at low frequencies for all of the optimization methods except for the AC method. At higher frequencies the standard deviation tends to increase, however, the ACLD method still achieves the lowest value. For a rear bright zone, the standard deviation is low for all four optimization methods at frequencies below around 80 Hz. At higher frequencies the AC method has a much higher standard deviation and, once again, ACLD has the lowest value at higher frequencies.

It is also interesting to observe the specific sound distribution in each zone and, therefore, the pressure is evaluated along the lines shown in the two control zones in Fig. 4. The resulting pressures for the four optimization methods when producing either a front or rear bright zone are shown in Fig. 5. From Fig. 5a it can be seen that AC has a significant dip in the sound pressure at the centre of each evaluation line, which helps to explain the high levels of standard deviation shown in Fig. 3. When producing a front bright zone LS, ACP and ACLD all show similar results with a lower level of pressure variation on the front evaluation line. When producing a rear bright zone it can be seen that the pressures on the rear line vary less for the ACLD method compared with all three other methods.

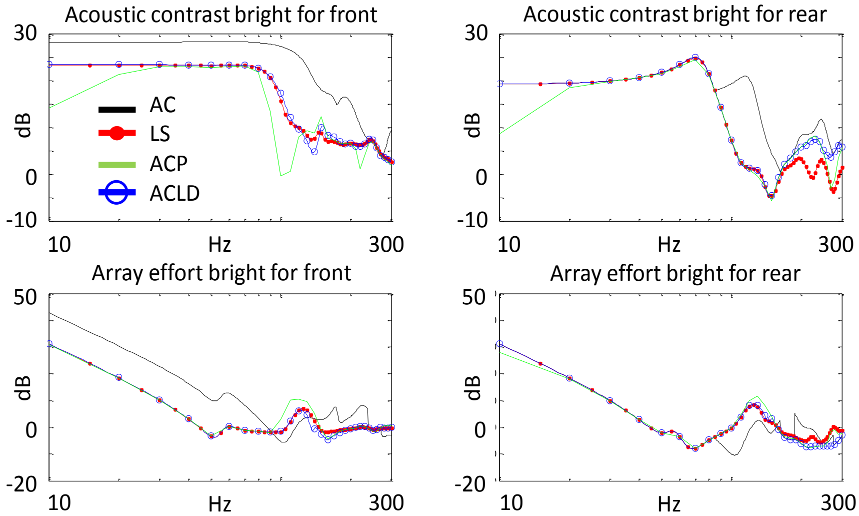


Figure 2: The acoustic contrast and array effort for the car audio loudspeaker array when producing a front bright zone (left hand plot) and a rear bright zone (right hand plots).

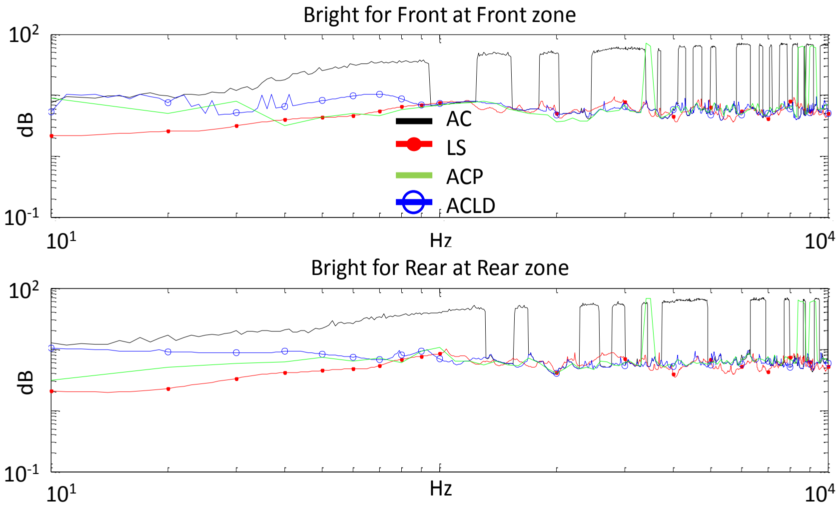


Figure 3: Standard deviation (Eqn (3)) in each zone for the car audio loudspeaker array.

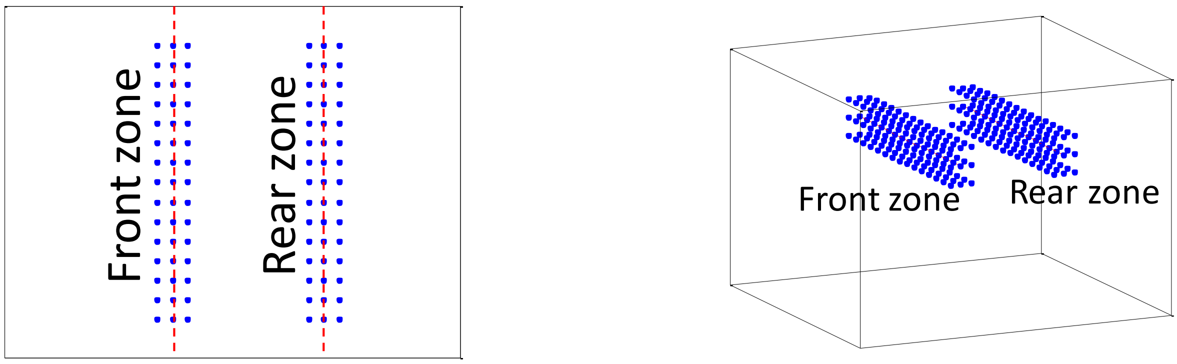
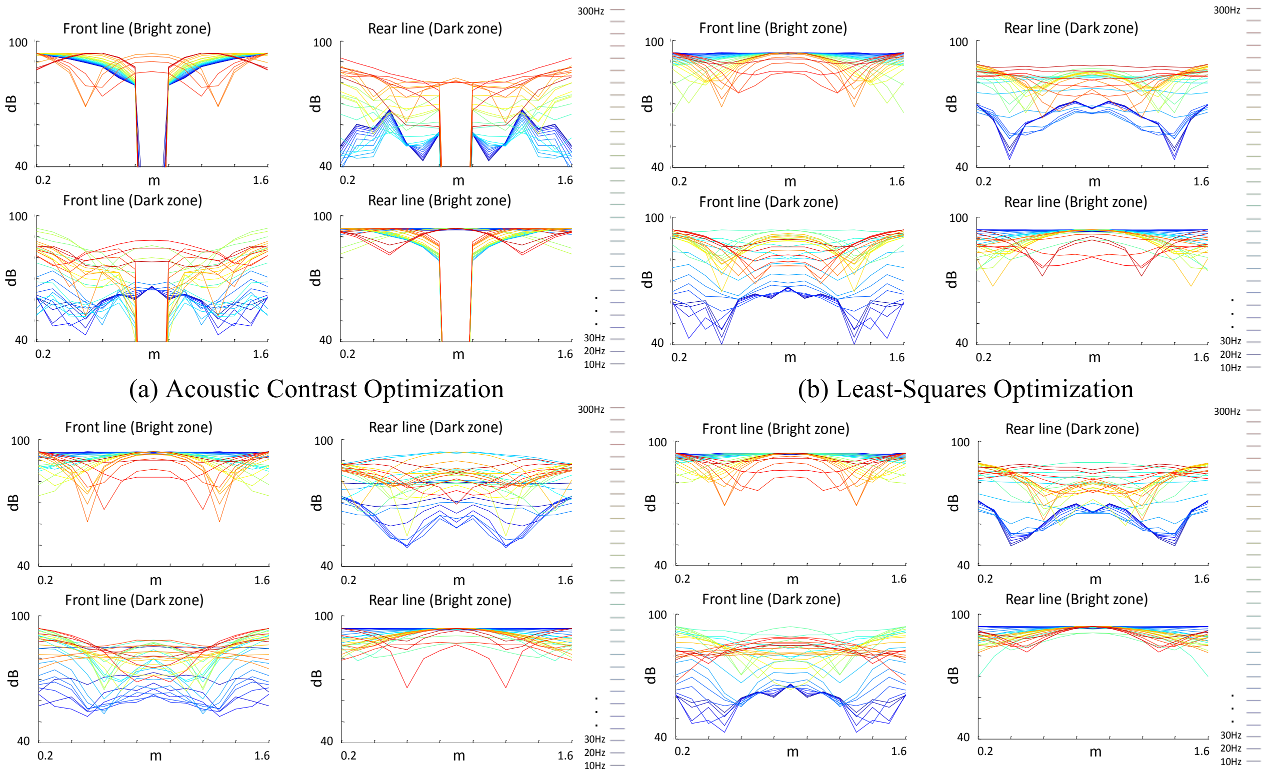


Figure 4: Evaluation lines at front zone and rear zone.



(a) Acoustic Contrast Optimization (b) Least-Squares Optimization

(c) Acoustic Contrast with Planarity (d) Acoustic Contrast with Limited Sound Difference

Figure 5: The sound distribution produced by the car audio loudspeaker array.

3.2 Headrest array

It is difficult to simulate the sound field at high frequencies in an enclosed space using the modal model because of the large number of acoustical modes required. However, due to the small distance between the control zone and the headrest loudspeakers, the response will be dominated by the direct sound and, therefore, can be approximated by the free field monopole response if we neglect the influence of the finite sized loudspeakers, the head and the seat which are in the near field of the array.

For the LS method, the target pressure vector is defined as

$$\begin{cases} \boldsymbol{p_{T\_B}} = \boldsymbol{Z_{B'}}\,\vec{\mathbf{1}} \\ \boldsymbol{p_{T\_D}} = \vec{\mathbf{0}} \end{cases}, \tag{25}$$

where $\mathbf{Z}_{B'}$ is the transfer response matrix composed of the response between all of the points in the bright zone and loudspeakers 1, 3, 5 and 7 in Table 3 in the case of a bright front zone, or loudspeakers 9, 11, 13 and 15 in the case of bright rear zone.

For the ACLD method the Lagrange multiplier which governs the constraint on the limited sound differences, $\lambda_{LD,}$ has been defined to ensure that the standard deviation is less than 10.54 dB at each frequency.

3.2.1 *Acoustic contrast and array effort*

The acoustic contrast and array effort for headrest loudspeaker array optimized using the four optimization methods are shown in Fig. 6. For both front and rear bright zones the acoustic contrast achieved by the AC and ACLD methods is high compared to LS and ACP, particularly at frequencies below around 1 kHz. ACP is very low at low frequency, but becomes close to the AC and ACLD methods at higher frequencies. The LS method consistently achieves a lower acoustic contrast than the other methods.

As expected, the array effort required by the AC and ACLD methods is significantly higher than LS and ACP at low frequencies, but then gradually decreases as frequency increases. The array effort required by the LS method decreases more slowly with increasing frequency, such that it becomes similar in level to the other three methods at high frequency.

3.2.2 *Standard deviation of sound pressure and sound distribution*

The standard deviation of the sound pressure within the bright zone and the sound pressure distribution along the evaluation lines shown in Fig. 4 are shown in Figs. 7 and 8 respectively.

From Fig. 7 it can be seen that the standard deviation of AC is the highest at frequencies below 1 kHz, followed by ACLD, ACP and LS. Above 1 kHz, AC is also high because of a lot of peaks. ACP shows a few narrowband peaks, while LS and ACLD are almost the same and have a much lower standard deviation on average.

From the pressure distributions shown in Fig. 8 it can be seen that AC and ACP have a significant dip in the sound pressure at a number of frequencies. This is consistent with the standard deviation results presented in Fig. 7. On the other hand, LS and ACLD show no significant dip in the sound pressure distribution.

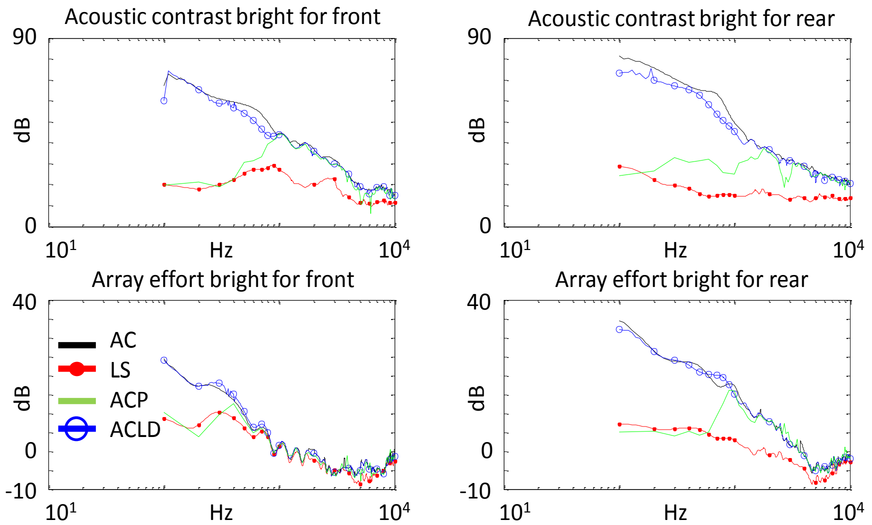


Figure 6: The acoustic contrast and array effort for the headrest loudspeaker array when producing a front bright zone (left hand plot) and a rear bright zone (right hand plots).

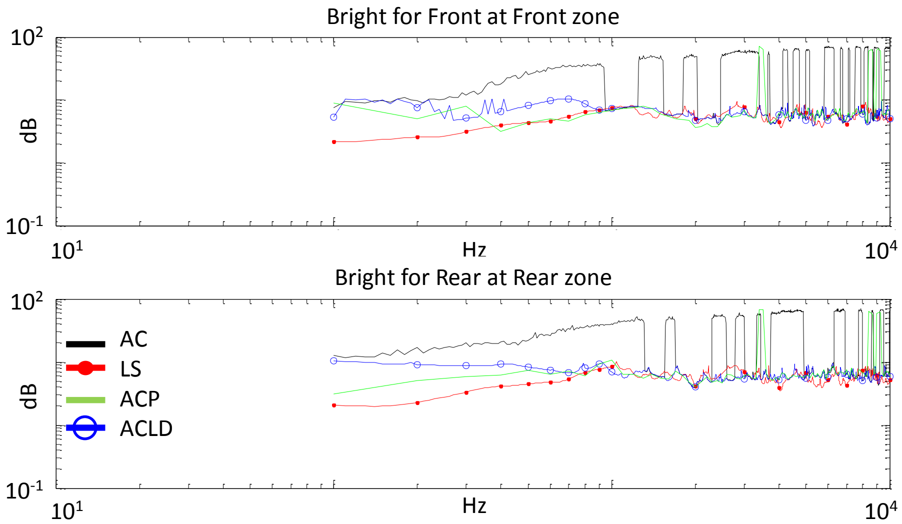
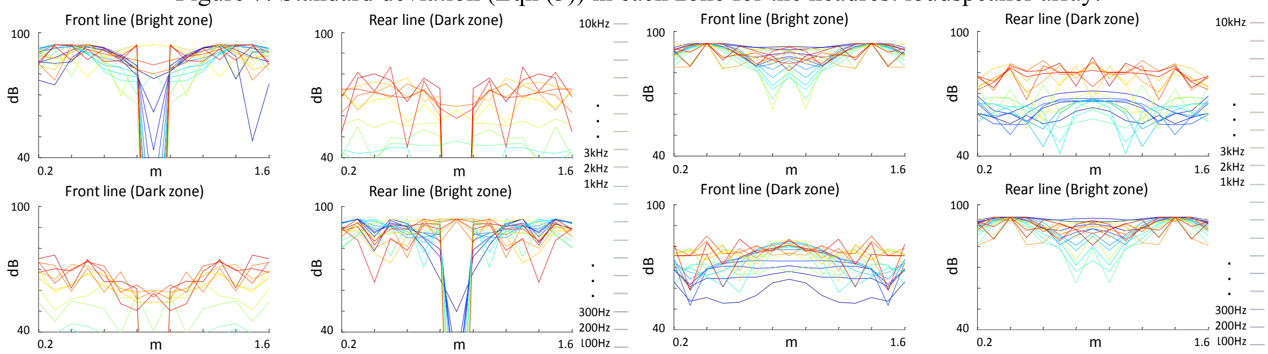
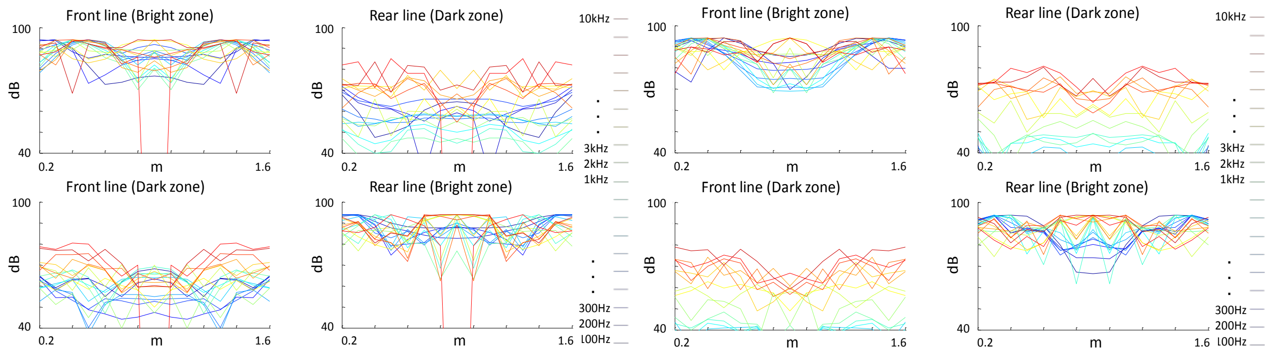


Figure 7: Standard deviation (Eqn (3)) in each zone for the headrest loudspeaker array.



(a) Acoustic Contrast Optimization

(b) Least-Squares Optimization



(c) Acoustic Contrast with Planarity (d) Acoustic Contrast with Limited Sound Difference

Figure 8: The sound distribution produced by the car audio loudspeaker array.

4 CONCLUSIONS

The optimization of personal audio systems which aim to reproduce sound in one region whilst minimizing the sound reproduced in another region has previously focused on either maximizing the acoustic contrast or reducing the error between a target pressure and the reproduced pressure, or some combination of these two. When maximizing the acoustic contrast, although the optimization is straightforward to setup, the pressure in the bright zone may have a large spatial variation. Conversely, by minimizing the error between a target field and the reproduced sound field the pressure variation can be limited, but it is no longer straightforward to setup the optimization to also achieve a high level of acoustic contrast. This paper introduces an optimization method which maximizes the acoustic contrast with a constraint that limits the differences in the sound pressure such that the spatial distribution of sound in the bright zone is limited. This method is called Acoustic Contrast with Limited Sound Differences (ACLD).

In the context of the car cabin personal audio application the performance of the proposed ACLD optimization method has been compared to AC, LS and ACP optimization methods. For the low frequency car audio loudspeaker array it has been shown that the ACLD optimization method achieves a similar level of acoustic contrast and bright zone pressure variation to the LS and ACP methods. However, since it only requires the definition of a single, frequency dependent, Lagrange multiplier it is more straightforward to setup than the LS method, which requires the definition of a target sound field, and the ACP method, which requires the definition of a number of parameters and the calculation of two inverse problems. By reducing the complexity of setting up the sound field control problem, ACLD reduces the difficulties in achieving a suitable compromise between the accuracy of reproduction or planarity and the acoustic contrast, which are experienced in the LS and ACP methods respectively.

For the headrest loudspeaker array, which is designed to operate at higher frequencies, it has been shown through the results of the presented simulations that the ACLD method is not only more straightforward to setup than the LS and ACP methods, but it also achieves a significantly higher acoustic contrast which is almost the same as AC whilst limiting the variation in the sound field within the bright zone compared to the AC method.

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