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PERSONAL AUDIO WITH MULTIPLE DARK ZONES

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ABSTRACT

When one person is listening to audio reproduced using loudspeakers mounted in a headrest, the leakage of sound to other people sat around them is of concern. This work considers providing personal audio for the listener by use of a local array of acoustic sources driven in such a way as to maintain the reproduced levels in the seat, in the so-called 'bright zone', whilst minimising the levels experienced by others sat close by, in the so-called 'dark zones'. The investigations carried out are an extension to previous work, which looked at maximising the difference in levels between the bright zone, in the seat, and a single adjacent dark zone. Here the problem of multiple dark zones leads to investigations into different geometrical arrangements of the source array. It is shown that minimising the sound power radiated by the local array while constraining the reproduced level in the bright zone is an effective method of achieving isolation when the dark zones are numerous. The findings of the investigations are used to design an optimal source arrangement, for which the isolation performance is verified with BEM models.

INTRODUCTION

In certain environments such as aircraft and cars, it may be unsafe for individuals to listen to audio using headsets, since this may prevent the wearer from hearing important announcements and may also be uncomfortable over long periods of time. Therefore it is desirable to use loudspeakers mounted in the headrest of the seat for the reproduction of sound, although this approach suffers from problems with leakage of sound to those around.

This work looks at using a local array of sources in the headrest to attempt to faithfully reproduce the audio in one seat, while minimising the leakage of sound to seats nearby so that the each seat provides personal, isolated audio. Such scenarios can occur when there is more than one row of seats positioned close together, as is often the case in aircraft. Previous work [1] has looked at the problem when there are just two adjacent seats, where audio is reproduced in one of the seats, termed the ‘bright zone’, while the levels are reduced in the adjacent seat, termed the ‘dark zone’. Here the work is extended to consider the problem when there is more than one dark zone, so that the leakage of sound to multiple seats is minimised.

The performance of three different control approaches for increasing the isolation are evaluated in this work, using simulations in which multiple dark zones are defined around a single bright zone and the improvement in isolation for each approach predicted. The performance of each approach is evaluated in terms of the *acoustic contrast* achieved, which is the ratio of the mean square pressures in the bright zone to the mean squares pressures in the dark zones, such that a large acoustic contrast indicates good isolation performance.

The particular problem of concern in this work is shown in a diagram in Figure 1, where the geometrical arrangement used is depicted including the locations of the sources and sensors employed in the simulations and experiments undertaken here. The dimensions are measured from a pair of adjacent airline-style seats, for which loudspeakers have been attached to the headrests. Three seats are shown in the diagram, where one of the seats corresponds to the bright zone and the others are the two dark zones, with one of these dark zones located to the side of the bright zone (Dark Zone A), and one located in front (Dark Zone B), separated from the bright zone by a typical seat pitch of 0.79m [2]. In each zone there are four microphones, where two microphones are clamped to the sides of the headrest and two located at the positions of the ears of those sat in the seats. Although in some control approaches the microphones are not used in the calculation of the optimal filters, these microphones are used for the calculation of performance in terms of the acoustic contrast between these seats and the bright zone, and by spreading microphones around each seat predictions of the average levels experienced in that seat can be made. In this work only the single-sided problem will be looked at, where we assume that the audio reproduced with the loudspeakers on one side of the headrest in the bright zone is uncorrelated with that reproduced on the opposite side, so that only one side is required to be simulated due to the fact that the problem is symmetrical.

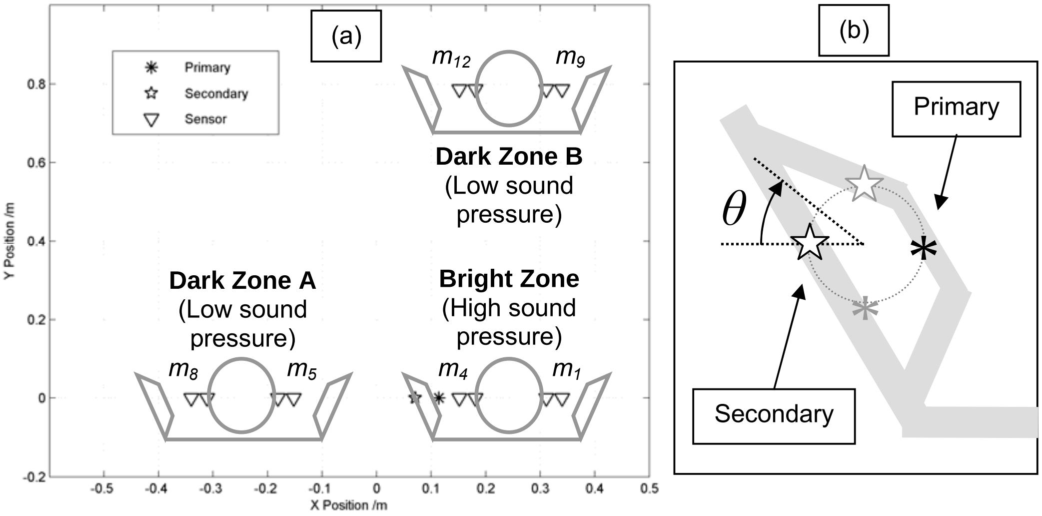

Figure 1 - (a) Diagram of the geometrical arrangement of sources and microphones used in the simulations, (b) Diagram of rotation of primary and secondary source pair

In the majority of this work, free-field monopole simulations are used to identify the source arrangement that gives the greatest average acoustic contrast for both dark zones. Three different control approaches are investigated for each arrangement, to determine the best strategy when there are multiple dark zones present. The results are then used to model a real pair of adjacent seats with the source positions corresponding to this optimal arrangement found from the monopole simulations, which is then used in a more sophisticated BEM simulation. This allows predictions of the performance when there are reflective and absorptive surfaces present, which is more representative of the real system.

CONTROL APPROACHES

The three different control approaches evaluated in this work are discussed here, with some comparisons between the behaviours of each.

Contrast Maximisation

With this approach, the difference in the mean square pressure in the bright and dark zone, or the *acoustic contrast*, is directly maximised. For a single frequency, this can be defined as the ratio:

$$\alpha = \frac{\boldsymbol{p}_{\mathrm{b}}^{\mathrm{H}}\,\boldsymbol{p}_{\mathrm{b}}}{\boldsymbol{p}_{\mathrm{d}}^{\mathrm{H}}\,\boldsymbol{p}_{\mathrm{d}}} \tag{1}$$

Here $\boldsymbol{p}_b$ is a vector of complex pressures in the bright zone, i.e. m_1 to m_4 in Figure 1, and $\boldsymbol{p}_d$ is a vector of complex pressures in both of the dark zones, i.e. m_5 to m_{12} in Figure 1. Since the pressure arriving at a sensor due to a single source is related to the complex source volume velocity by the complex impedance associated with the path, the vectors $\boldsymbol{p}_b$ and $\boldsymbol{p}_d$ due to multiple sources can be written $\boldsymbol{p}_b = \boldsymbol{Z}_b\boldsymbol{q}_c$ and $\boldsymbol{p}_d = \boldsymbol{Z}_d\boldsymbol{q}_c$ respectively. The quantity $\boldsymbol{q}_c$ is the [N-by-1] vector of complex source strengths which are to be optimised, and $\boldsymbol{Z}_b$ and $\boldsymbol{Z}_d$ are [M-by-N] matrices of complex impedances to the bright and dark zone sensors, where M is the number of sensors and N is the number of sources. By combining these expressions with equation (1), the acoustic contrast can now be expressed as:

$$\alpha = \frac{\boldsymbol{q}_c^{\,H} \boldsymbol{Z}_b^{\,H} \boldsymbol{Z}_b \boldsymbol{q}_c}{\boldsymbol{q}_c^{\,H} \boldsymbol{Z}_d^{\,H} \boldsymbol{Z}_d \boldsymbol{q}_c} \tag{2}$$

As Choi and Kim show [3], this ratio is maximised if the vector of complex source strengths is equal to the eigenvector of the matrix $[\boldsymbol{Z}_d^{H}\boldsymbol{Z}_d]^{-1}\,\boldsymbol{Z}_b^{H}\boldsymbol{Z}_b$ associated with the largest eigenvalue.

Control Effort Minimisation

An alternative cost function also developed by Choi and Kim is what the authors term the brightness constraint, where the control effort is explicitly minimised while a constraint exists to maintain the reproduced levels in the bright zone. The control effort can be described as the mean square source strengths, which may be written as $\boldsymbol{q}_c^{H}\boldsymbol{q}_c$. The ratio to be maximised in this case becomes:

$$\alpha = \frac{\boldsymbol{q}_c^{\,H} \boldsymbol{Z}_b^{\,H} \boldsymbol{Z}_b \boldsymbol{q}_c}{\boldsymbol{q}_c^{\,H} \boldsymbol{q}_c} \tag{3}$$

The vector of source strengths which maximises this ratio is the eigenvector of the matrix $\boldsymbol{Z}_b^{h}\boldsymbol{Z}_b$ corresponding to the largest eigenvalue.

Sound Power Minimisation

Another control strategy is to minimise the sound power output of the array directly, while constrained to maintain the reproduced levels in the bright zone. The cost function is obtained from the definition of the sound power W for multiple monopole sources, which can be written as $W = {}^{1}\!/_{2}\ \boldsymbol{q}_c^{H}\,\mathbf{Re}\{\boldsymbol{Z}_q\}\boldsymbol{q}_c$. Here $\boldsymbol{Z}_{\boldsymbol{q}}$ is a matrix of transfer impedances from each source to the pressure at every other source position, in other words the contribution of pressure at each of the source positions due to each source in turn, divided by the volume velocity of the source. The denominator used in Eq. (2) is replaced by this expression for the sound power, and so the ratio to be maximised becomes:

$$\alpha = \frac{2\boldsymbol{q}_c^{\,H} \boldsymbol{Z}_b \boldsymbol{q}_c}{\boldsymbol{q}_c^{\,H}\, \mathbf{Re}\left\{\boldsymbol{Z}_q\right\} \boldsymbol{q}_c} \tag{4}$$

The solution to this expression in which the ratio α is maximised will be equal to the eigenvector associated with the largest eigenvalue of the matrix $2\ [\mathbf{Re}\{\boldsymbol{Z}_q\}]^{-1}\ \boldsymbol{Z}_b$. For simplicity, the factor of 2 can be ignored since the eigenvalues themselves are not employed.

Comparison of different cost functions

When analysing the performance of the different approaches in terms of the acoustic contrast achieved, the contrast maximisation approach will always yield the maximum performance. However, the problem with the contrast maximisation approach is that the solution may result in regions of high pressure levels away from the defined dark zones. To avoid this problem, a more straightforward approach would be to attempt to minimise the sound power output of the array while maintaining the reproduced levels in the bright zone. In this way, the acoustic contrast is maximised for all regions of space and therefore the solution will be more appropriate when there are a large number of dark zones located close to the bright zone.

The control effort minimisation seeks solutions that give the largest reproduced pressure in the bright zone using the weakest possible individual source strengths. This will penalise self-cancelling solutions, which is not always desirable since self-cancelling source arrays may give a lower sound power output.

MONOPOLE SIMULATIONS

In the simulations presented here, it is assumed that all sources act as monopoles in an anechoic environment so that free field radiation conditions apply. This provides an estimate of the limits of performance with each arrangement, so that the results are not applicable for just one particular headrest design but can be used to gain insight into the generalised problem.

In defining the arrangement used in the simulations, there are a finite number of possible locations for the primary source. In this work, it is assumed that the primary source is mounted on one of the wings of the headrest attached to the bright zone seat. In this arrangement the mounting is straightforward and due to the proximity of the loudspeakers to the ears of those sat in the seat, the perceived levels in the seat can be high without needing to drive the loudspeakers hard. Typically it is desirable to locate the secondary source as close as possible to the primary source in active control applications, and therefore the distance separating the primary and secondary source in the first set of simulations is maintained at the minimum of 4cm, which is the separation distance of a pair of small 4” full-range drivers used in earlier experiments when mounted face-to-face [4].

The first set of simulations considered the effect of rotating the primary and secondary source pair around the central pivot of this pair, as shown in the diagram in Figure 1 (b). For a number of discrete values of orientation angle θ, the soundfield surrounding the bright zone is computed before and after optimisation, where the three different cost functions are employed to find the optimal complex source strengths. Figure 2 shows the results for these simulations in terms of the acoustic contrast averaged for both dark zones shown in Figure 1, and averaged over frequency up to 2kHz, as a function of source orientation angle. Also shown in Figure 2 is the sound power output of the array averaged over frequency as a function of source orientation angle.

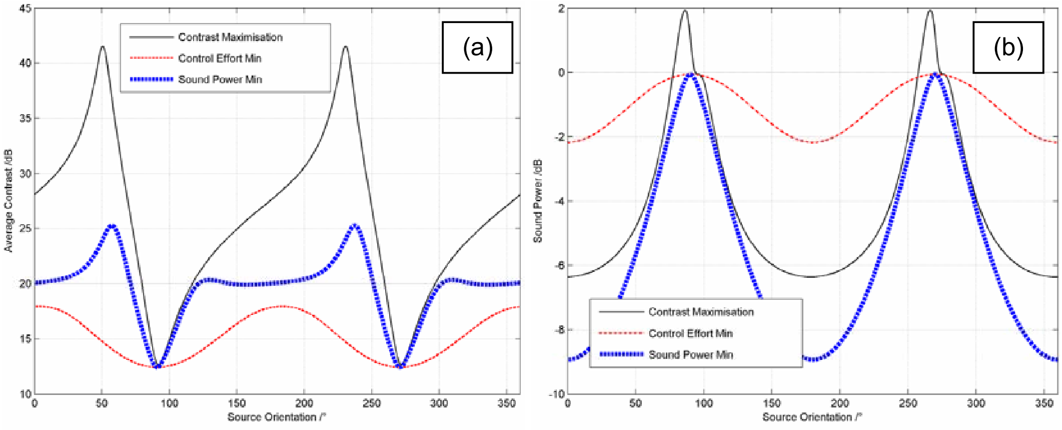

Figure 2 - (a) Average acoustic contrast achieved with the different control approaches as a function of source orientation angle, (b) Average sound power output of the array for the different control approaches as a function of source orientation angle

It can be seen from Figure 2 that the optimal source orientation angles are around 50 to 60°, where good isolation performance is achieved without the high sound power output levels that occur around 90°. The orientation angles of 50 to 60° correspond to the case where the nulls in the directivity pattern of the array line up with the locations of the two dark zones. As expected, the results from 180° to 360° are the same as the results from 0° to 180° when both sources are active, since the arrangement of the array is identical when rotated by 180°. The high sound power output at 90° is due to the null in the directivity which this approach gives, and which is directed towards the bright zone so that the array must increase the output level in order to maintain the reproduced levels. Contour plots of the soundfield at 500Hz are provided in Figure 3 for sources placed at the orientation angle of 57°, where the contrast maximisation and the sound power minimisation approaches are used, respectively. Figure 4 shows the acoustic contrast and sound power output for all three approaches as a function of frequency, when the source orientation angle is fixed at 57°.

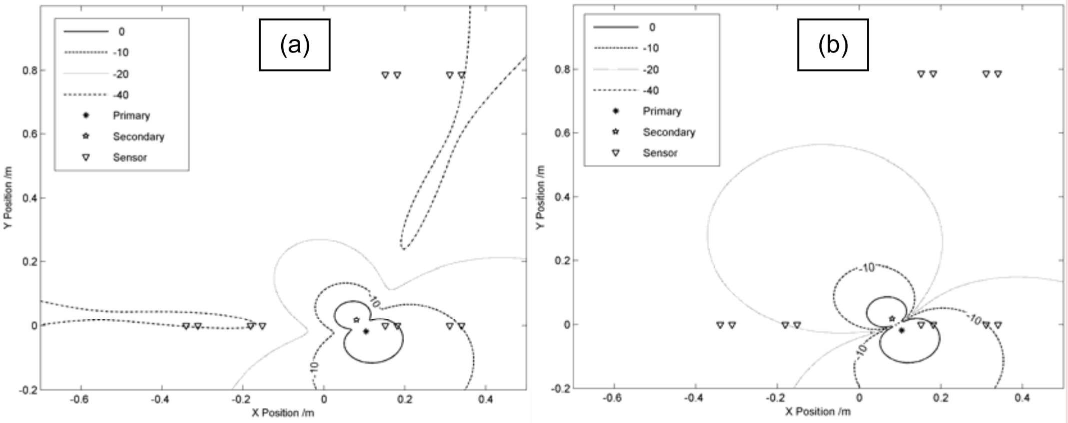

Figure 3 - (a) Contour plot of the sound pressure level at a frequency of 500Hz for a source orientation angle of 57° using the contrast maximisation approach, and (b) using the sound power minimisation approach in dB

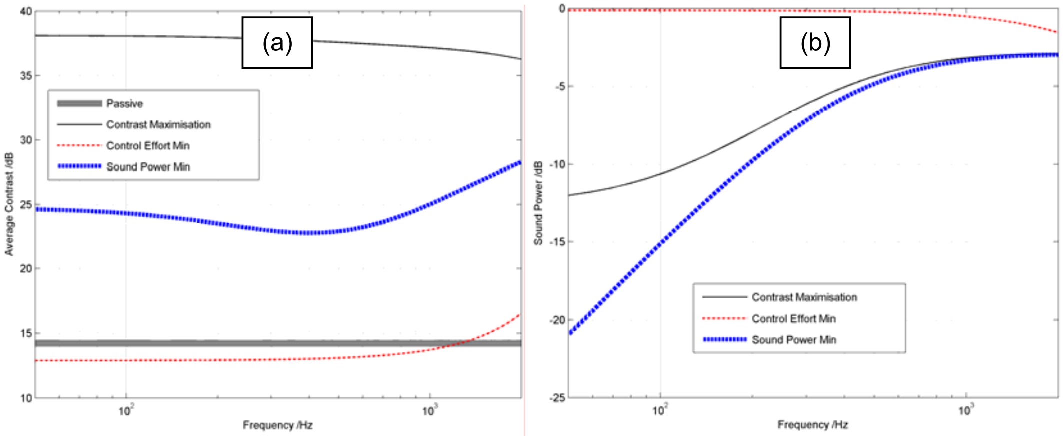

Figure 4 - (a) Passive and active contrast averaged for both dark zones as a function of frequency, using all three control approaches, (b) Sound power output of the two-source array as a function of frequency, using all three control approaches

From these results, it can be concluded that the sound power minimisation approach achieves an average of 10-15dB less acoustic contrast than that achieved by directly maximising the acoustic contrast, while obtaining only a small decrease in the overall sound power output, especially at high frequencies. The control effort minimisation approach is shown to achieve poor performance in terms of both the acoustic contrast and the sound power output, and is therefore not considered any further in this work.

BEM SIMULATIONS

A BEM simulation of the source arrangements of interest was developed to verify that the suggested solution applies to a real seat when there are multiple reflecting and absorbing surfaces present. An acoustic mesh is constructed of a pair of airline seats that were obtained for this work (Figure 6(b)), and the sources are represented by a non-zero velocity boundary condition being defined on certain elements of this mesh. In this case the source array consisted of a cylinder in which the circles at either end act as separate sources. The Variational BEM was employed for this work, since this method does not suffer from such severe problems with thin-walled structures compared to the Direct BEM (e.g. [5]).

Figure 5 shows the soundfield after contrast maximisation at a frequency of 500Hz and 1550Hz when the primary and secondary source pair are fixed at the optimal orientation of 57°. The average acoustic contrast before and after control for the two dark zones is shown in Figure 6. Below 800Hz, the predicted isolation performance is slightly greater than the performance predicted in the monopole simulations, which can be attributed to the reflections from the headrest of dark zone A and the presence of the head. Above 800Hz the distance separating the sources becomes comparable with 1/10th of a wavelength and so the regions of low pressure become more localised and the performance is seen to drop.

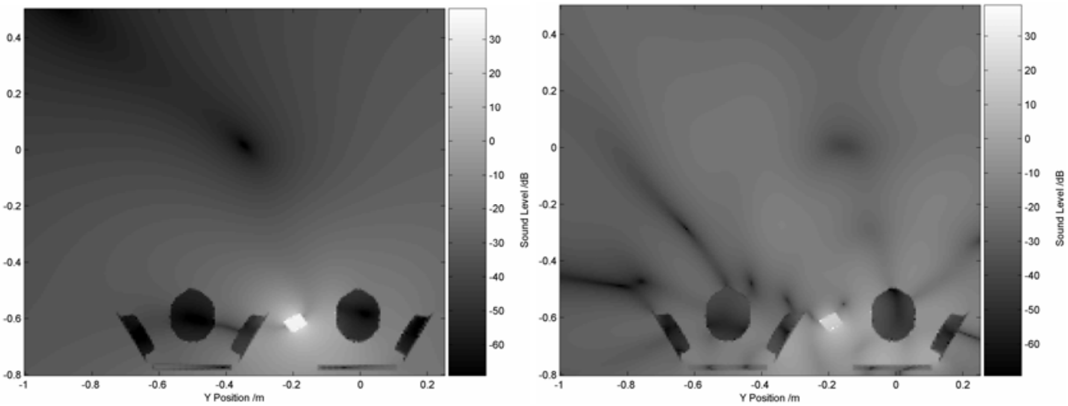

Figure 5 - Soundfield plot at 500Hz (a) and 1550Hz (b) using results from the BEM simulation where a single secondary source is used at an angle of 57°

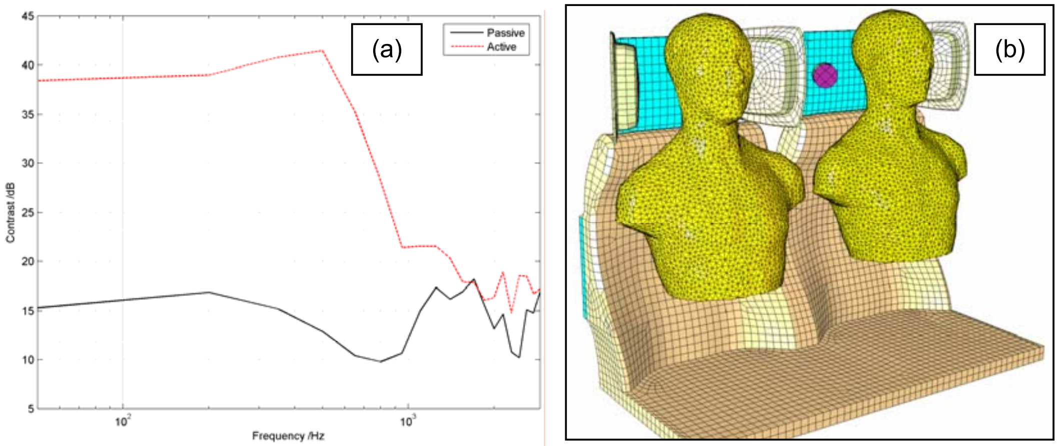

Figure 6 - (a) Predicted passive and active contrast averaged over both dark zones as a function of frequency with a source orientation angle of 57°, (b) Image of the mesh used in BEM

CONCLUSIONS

The sound power minimisation approach has been shown to provide good performance when multiple dark zones are present, although the contrast maximisation approach is able to obtain significant increases in the acoustic contrast for this particular geometry, with little increase in the sound power output. As the number of dark zones increases, the contrast maximisation solution will approach that of the sound power minimisation solution. The solutions that result in the minimum sound power output are those in which the sources are closely spaced and driven such that the array is as self-cancelling as possible. Control effort minimisation is not a suitable approach for this work, since sound power output is not closely related to the control effort, and the resulting isolation performance is poor. The optimal source arrangements are shown to be those where the nulls in the directivity of the array are steered away from the bright zone and towards the dark zones, such that control can be enhanced in certain regions by a simple rotation of the array.

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