DTU Library

A comparison of two strategies for generating sound zones in a room.

Jacobsen, Finn; Olsen, Martin; Møller, Martin; Agerkvist, Finn T.

Published in:
Proceedings of 18th International Congress on Sound and Vibration

Publication date:
2011

Citation (APA):
Jacobsen, F., Olsen, M., Møller, M., & Agerkvist, F. T. (2011). A comparison of two strategies for generating sound zones in a room. In *Proceedings of 18th International Congress on Sound and Vibration* International Institute of Acoustics and Vibration.

18TH INTERNATIONAL CONGRESS ON SOUND & VIBRATION
ICSV18
RIO DE JANEIRO
BRAZIL
10–14 JULY 2011

A COMPARISON OF TWO STRATEGIES FOR GENERATING SOUND ZONES IN A ROOM

Finn Jacobsen, Martin Olsen, Martin Møller and Finn Agerkvist

Acoustic Technology, Department of Electrical Engineering, Technical University of Denmark, DK-2800, Kgs. Lyngby, Denmark
e-mail: fja@elektro.dtu.dk

For some purposes it may be of interest to generate sound zones with different acoustic properties in a room. This paper compares two strategies for generating such zones. One method is based on 'contrast optimisation': the idea is to maximise the ratio of the potential energy in a 'bright' (ensonified) zone to the potential energy in a 'dark' (quiet) zone with a given source configuration. An alternative method based on 'sound field synthesis' has the more ambitious goal to control the sound field in the bright zone in detail, for example, to generate a plane wave that propagates in a certain direction. The two methods are analysed theoretically and examined through simulations and experimentally.

1. Introduction

It may be desirable to control the sound field in a room to such an extent that it can be used as a multipurpose room in which different audio-visual events can be experienced simultaneously by several users, e.g., watching home cinema, listening to music, playing computer games, etc., without disturbing each other. If one could generate 'bright' and 'dark' zones by driving a number of loudspeakers with appropriate amplitudes and phase angles, it follows from linear superposition that it would also be possible to generate zones with different sound programmes that would not disturb each other. The purpose of this paper is to examine and compare two different control strategies for generating such sound zones. The investigation is limited to the generation of two zones, a bright one and a dark one, and there are no restrictions on the remaining part of the sound field.

2. Outline of theory

Numerous methods for controlling sound fields in free space and in rooms have been described in the literature. This investigation concentrates on two different techniques, a fairly straightforward one requiring a minimum of control sources, and a more sophisticated one requiring what at the moment might seem to be an unrealistic number of control sources.

2.1 Contrast optimisation

Active noise control is often based on minimising a cost function, usually the potential sound energy, in the region where quietness (or 'darkness') is required. Under some conditions this can be achieved using adaptive filters that change the complex strengths of a number of control sources in order to minimise error signals picked up by microphones in the controlled zone, and this method can also be used for control of sound fields for a more general purpose.[1] However, the number of microphones that are necessary for controlling the sound field in a given region in three dimensions (3D) increases with the frequency cubed, which is clearly not practical except at very low frequencies. A more convenient approach, adopted in this investigation, relies on measured transfer functions between all sources and the sound pressure in a grid of points in the zones to be controlled.

The chosen control strategy is based on 'constrained optimisation' and essentially follows Choi and Kim.[2] There are two zones of concern, either in free space or in a room, and the task is to maximise the 'contrast' between the bright and the dark zone or – expressed more precisely – to maximise the potential energy in the bright zone subject to the constraint that the potential energy in the dark zone is constant. This can be expressed in terms of the Lagrange function as

$$L(\mathbf{q},\alpha)=\mathbf{q}^H\mathbf{G}_\mathrm{B}^H\mathbf{G}_\mathrm{B}\mathbf{q}-\alpha\left(\mathbf{q}^H\mathbf{G}_\mathrm{D}^H\mathbf{G}_\mathrm{D}\mathbf{q}-L_0\right), \quad (1)$$

in which $\mathbf{q}$ is a column vector with the unknown strengths of the control sources, $\mathbf{G}_\mathrm{B}$ and $\mathbf{G}_\mathrm{D}$ are matrices of transfer functions between control sources and positions in the bright and dark zone, H denotes the Hermitian transpose, L_0 is the desired potential energy in the dark zone, and α is the 'Lagrange multiplier'.[2-4] Note that $\mathbf{G}_\mathrm{B}^H\mathbf{G}_\mathrm{B}$ and $\mathbf{G}_\mathrm{D}^H\mathbf{G}_\mathrm{D}$ may be interpreted as spatial correlation matrices.[2,4] It can be shown that the set of source strengths that maximises the ratio of energies is the eigenvector of source strengths that corresponds to the largest eigenvalue of $\left(\mathbf{G}_\mathrm{D}^H\mathbf{G}_\mathrm{D}\right)^{-1}\mathbf{G}_\mathrm{B}^H\mathbf{G}_\mathrm{B}$.[5]

It is apparent that the method is very general, but obviously its performance can be expected to depend on the number of control sources and their distribution, on the frequency, on the size of the zones and the distance between them, and on possible reflections from the walls of a room.

Figure 1 shows some results of simulations under free-field conditions and in a room with sixteen monopoles. It can be seen that sixteen sources can generate zones with a substantial level difference under free-field conditions at low frequencies. However, the achievable level difference with a given configuration of sources and zones is reduced at high frequencies, and the performance is – not surprisingly – better under free-field conditions than in a room.

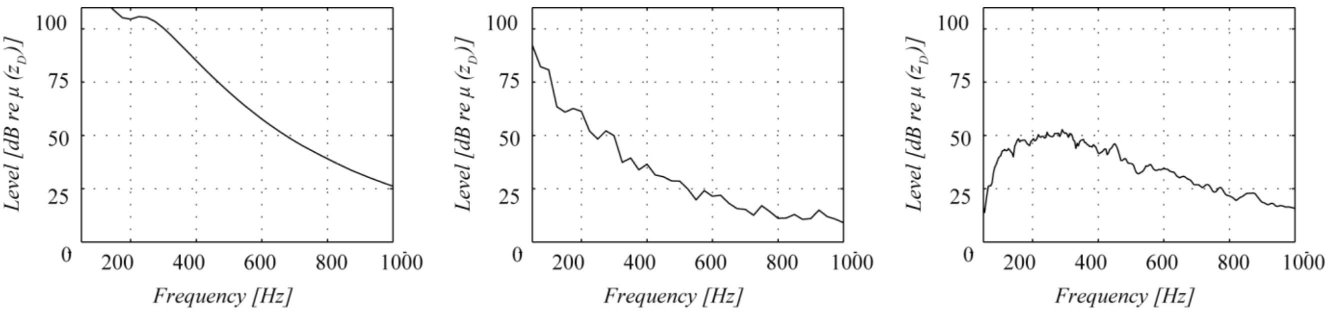


Figure 1. Simulation results obtained with contrast optimisation using sixteen monopoles on a circle with a radius of 1.8 m and zones with a radius of 0.5 m, with centres 1.8 m from each other. Left, level difference under free-field conditions; middle, level difference with a room acoustic model based on image sources; right, level difference with transfer functions measured in a strongly damped room.

2.2 Sound field synthesis

The idea of reproducing sound fields rather than just sound goes back to the late 1960s.[6] More recent examples include attempts to generate plane waves with monopoles in free space[7,8] and in a room.[9] Ambisonics is a reproduction technique based on spherical harmonics – but in principle limited to recreating the desired sound field at the centre of a spherical loudspeaker array under free-field condition.[10,11] Wave field synthesis is also a free-field technique; the idea is to record and reproduce propagating wave fronts.[12] Sound field reproduction techniques based on circular and spherical loudspeaker arrays have also been examined.[13] The sound field synthesis approach examined in this work is an extension of a method described by Wu and Abhayapala,[14] who studied generation of sound zones in 2D with a circular array of 2D monopoles (line sources). For 3D reproduction the zones must be spherical, and it is convenient if not strictly necessary that the sources are

3D monopoles (point sources) arranged on a spherical surface enclosing the global region. This work is restricted to '2.5D', which implies that the monopoles are arranged in a circular array, and our concern is limited to the resulting sound field in the plane of the loudspeaker array. Reflections from the walls can be taken into account,[15,16] but this is a complication, ignored in this paper.

The desired sound field in the bright zone should be expanded into a set of spherical functions based on a local coordinate system for the zone,

$$S_{\mathrm{B}}\left(r_{\mathrm{B}},\frac{\pi}{2},\varphi_{\mathrm{B}}\right)=\sum_{m=-\infty}^{\infty}A^{\mathrm{B}}_{|m|m}\,j_{|m|}(kr_{\mathrm{B}})Y^{m}_{|m|}\left(\frac{\pi}{2},\varphi_{\mathrm{B}}\right), \tag{2}$$

where (r_{B}, φ_{B}) is the position expressed in the local polar coordinate system in the plane $\theta=\pi/2$, k is the wavenumber, j_m is a spherical Bessel function of order m, and Y_n^m is a 'spherical harmonic'.[17] Note that the usual double summation over spherical harmonics as defined in Ref. 17 has been simplified because the expansion is restricted to 'sectoral harmonics'.

If the desired sound field is a plane propagating wave propagating in the direction $\varphi_{\mathrm{B}}=\varphi_0$ in the plane $\theta=\pi/2$ the coefficients of the expansion can be calculated analytically,[17]

$$A^{\mathrm{B}}_{|m|m}=4\pi i^{|m|}Y^{m}_{|m|}\left(\frac{\pi}{2},\varphi_0\right)^{*}, \tag{3}$$

where i is the imaginary unit and * denotes the complex conjugate. The dark zone is dealt with in the same way, but all the coefficients are zero.

Next, the local sound field coefficients should be translated to coefficients in the global coordinate system.[18] The translation matrix $\mathbf{T}_{\mathrm{B}}$ that relates the global coefficients to the local ones can shown to be[16]

$$\begin{aligned}T^{|m|m}_{\mathrm{B}|m'|m'}\left(\mathbf{r}_t\right)=i^{\left(|m-m'|+|m'|-|m|\right)}&\sqrt{\frac{1}{4\pi}\left(2|m|+1\right)\left(2|m'|+1\right)\left(2|m-m'|+1\right)}\begin{pmatrix}|m| & |m'| & |m-m'|\\ 0 & 0 & 0\end{pmatrix}\\ &\times\begin{pmatrix}|m| & |m'| & |m-m'|\\ -m & m' & \left(m-m'\right)\end{pmatrix}j_{|m-m'|}(kr_t)Y^{m-m'}_{|m-m'|}\left(\frac{\pi}{2},\varphi_t\right),\end{aligned} \tag{4}$$

where $\mathbf{r}_t=r_te^{i\varphi_t}$ is the vector between the origin of the global and the local coordinate system, m is the global index, m' is the local index, and

$$\begin{pmatrix}n_1\, n_2\, n_3\\ o_1\, o_2\, o_3\end{pmatrix}=\left(-1\right)^{\left(k_2-k_2\right)}\sqrt{\frac{1}{\left(N+1\right)!}\frac{k_1!k_2!}{k_3!}\frac{s_3!d_3!}{s_1!d_1!s_2!d_2!}}\sum_{l=0}^{k_3}\left(-1\right)^l\binom{k_3}{l}\left[s_1\right]_{k_3-l}\left[d_2\right]_{k_3-l}\left[s_2\right]_l\left[d_1\right]_l \tag{5}$$

is the Wigner 3j symbol,[19,20] in which

$$N=n_1+n_2+n_3;\ k_l=N-2n_l;\ s_l=n_l+o_l;\ d_l=n_l-o_l;\ \binom{k_3}{l}=\frac{k_3!}{l!\left(k_3-l\right)!};\ \left[x\right]_l=\frac{x!}{\left(x-l\right)!}. \tag{6}$$

A similar translation matrix, $\mathbf{T}_{\mathrm{D}}$, is determined for the dark zone. It should be mentioned that a direct implementation of the Wigner 3j symbol after Eq. (5) may give rise to numerical instabilities since extremely large numbers can occur. An alternative recursive technique may be more robust.[21]

A global translation matrix, $\mathbf{T}_{\mathrm{G}}$, is now established by stacking the individual matrices $\mathbf{T}_{\mathrm{B}}$ and $\mathbf{T}_{\mathrm{D}}$. The result is an overdetermined system of equations, $\mathbf{a}=\mathbf{T}_{\mathrm{G}}\mathbf{b}$, where $\mathbf{a}$ is a vector with the local coefficients for the two zones and $\mathbf{b}$ is a vector with the global coefficients. This matrix equation can be solved in the least-squares sense using the pseudoinverse matrix $\left(\mathbf{T}_{\mathrm{G}}^{H}\mathbf{T}_{\mathrm{G}}\right)^{-1}\mathbf{T}_{\mathrm{G}}^{H}$. Since the resulting global sound field in practice must be generated by an array of monopoles, the corresponding source strengths must finally be determined. In this work this is done by matching modes using a continuous loudspeaker concept and expanding the Green's function into the global set of coefficients.[22] This requires that the monopoles are placed equidistantly on a circle. An alternative method, not examined in this work, involves least-squares optimisation in a general geometry.[15,23]

Obviously all infinite series must be truncated. This implies a highest order of the spherical Bessel functions, which is linked to their largest argument, kr_G (where r_G is the radius of the global zone),[17,23] which, through simple sampling considerations, entails that $L > 2\lceil kr_G \rceil = \lceil c_G/(\lambda/2) \rceil$, where L is the number of control sources, c_G is the circumference, and λ is the wavelength.[16]

Figure 2 shows some results obtained at 1 kHz with 67 monopoles on a circle with a radius of 1.8 m, corresponding to the requirement mentioned above. As can be seen a level difference between the bright and the dark zone of about 40 dB is obtained, and it is clear from the plotted real part of the complex sound pressure that a plane propagating wave has been obtained. It should be mentioned that the performance of the synthesis technique depends on the direction of the propagating wave; it deteriorates if it is attempted to generate a wave that propagates in the direction towards (or away from) the dark zone.[16]

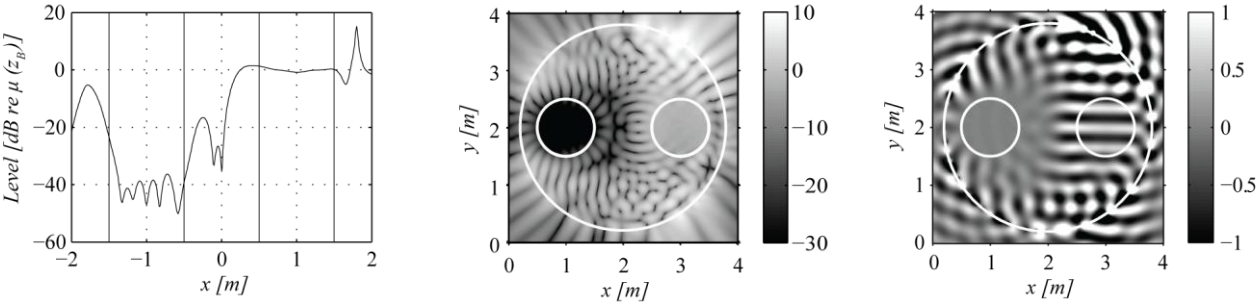


Figure 2. Results obtained with the synthesis approach at 1 kHz using 67 monopoles on a circle with a radius of 1.8 m. Left, sound pressure level along a line through the two zones (indicated by vertical lines); middle, sound pressure level; right, real part of complex pressure.

2.3 Comparison of the two approaches

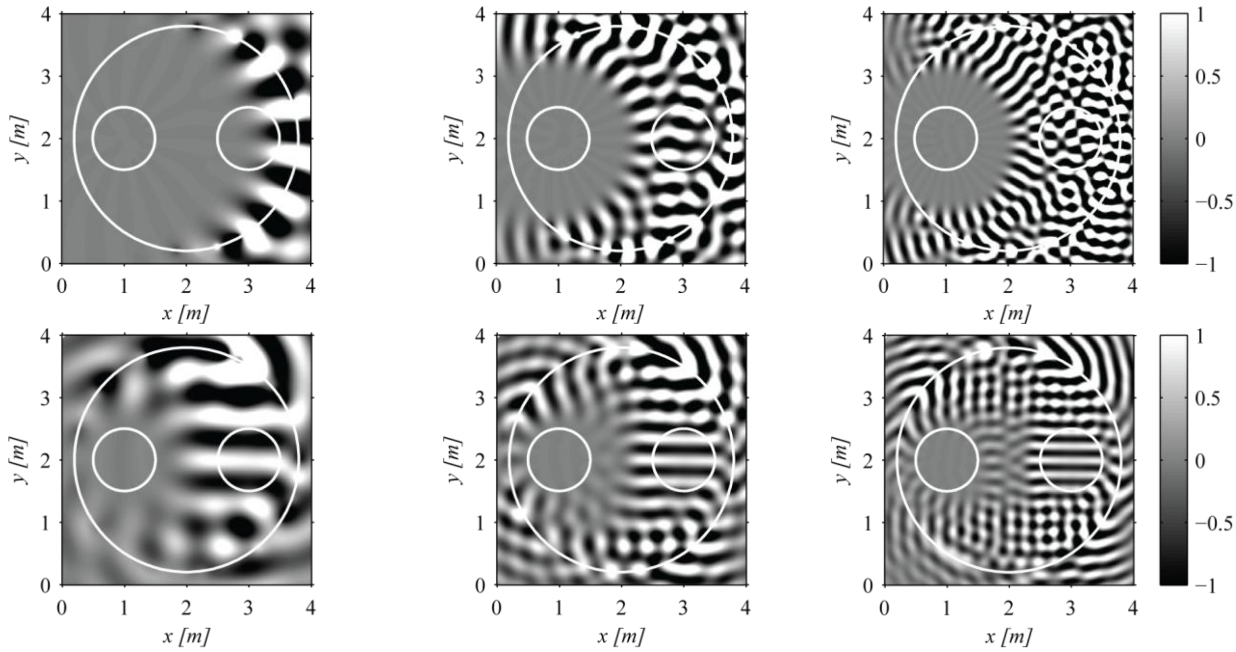
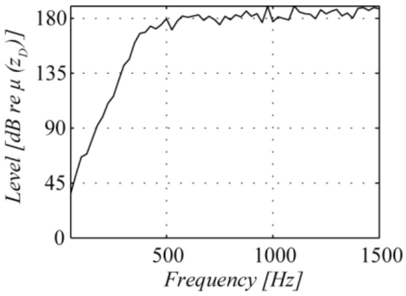


Figure 3. Real part of complex pressure obtained with a circular array of monopoles with a radius of 1.8 m under free-field conditions for two zones with a radius of 0.5 m; number of monopoles: $2\lceil kr_G \rceil + 1$. Top row, contrast optimisation; bottom row, the synthesis approach. Left column, 0.5 kHz; middle column, 1 kHz; right column, 1.5 kHz.

It is interesting to compare the performance of the two methods under identical conditions. The results shown in Fig. 3 have been calculated under the assumption of free-field conditions and with sufficiently many control sources to satisfy the conditions for the synthesis approach. As can be seen, the contrast optimisation method can successfully generate a large dark zone, but the resulting wavefronts in the bright zone come from erratic directions. By contrast, the synthesis approach has perfect control over the propagation of sound in the bright zone, but both the bright and the dark zones are smaller. Moreover, the level difference between the bright and the dark zone obtained using the contrast optimisation approach is far better than the level difference obtained using the synthesis approach, as demonstrated by Fig. 4.



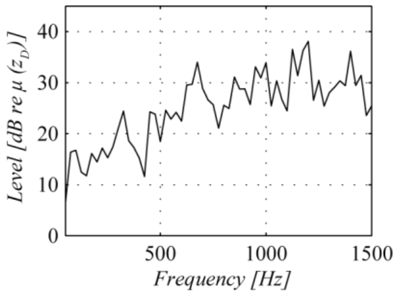


Figure 4. Level difference obtained with contrast optimisation (left) and the synthesis approach (right). The data correspond to Fig. 3.

3. Experimental results

Some experiments have been carried out in ‘Space Lab’ at the Technical University of Denmark. This is a heavily damped room with the walls covered by a 15 cm layer of foam and a free space of about 52 m^3. The room has been designed for ambisonic auralisation with 29 loudspeakers arranged approximately in a spherical array with a radius of 1.8 m.[24] Sixteen of the loudspeakers (two-way Dynaudio BM6P studio monitors) constitute a horizontal, circular array, and this was the loudspeaker array used in the experiments; see Fig. 5. All digital signal processing of the loudspeaker signals was made offline with MATLAB. The resulting sound field was sampled in the plane of the loudspeakers with a rectangular microphone array based on sixty ¼-inch microphones of type Brüel & Kjær (B&K) 4957 and a spacing of 7.5 cm. The microphone signals were analysed using a B&K ‘PULSE’ analyser with a 65 channel frontend. The microphones were placed in a plane, rectangular array with a 6×10 grid of dimensions 37.5×75 cm. In order to cover a measurement plane of dimensions 1.5×2.6 m the array was moved in a grid of 2 rows and 7 columns.

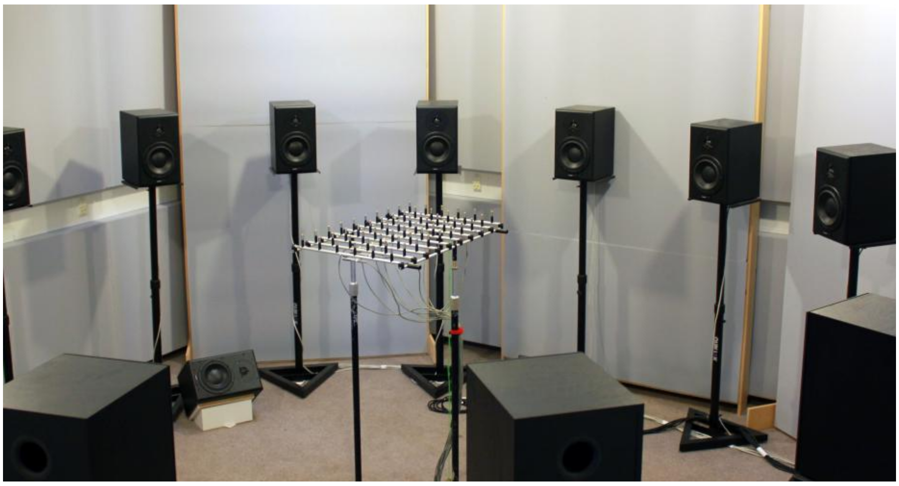


Figure 5. ‘Space Lab’ with 29 loudspeakers and the microphone array with 60 microphones.

3.1 Contrast optimisation

Typical experimental results obtained with the contrast optimisation approach using measured transfer functions are shown in Fig. 6. It is apparent that the achievable level difference is reduced at high frequencies, in agreement with the simulations. Nevertheless, level differences of more than 10 dB are obtained in relatively large zones at 1.5 kHz, and significantly more at low frequencies.

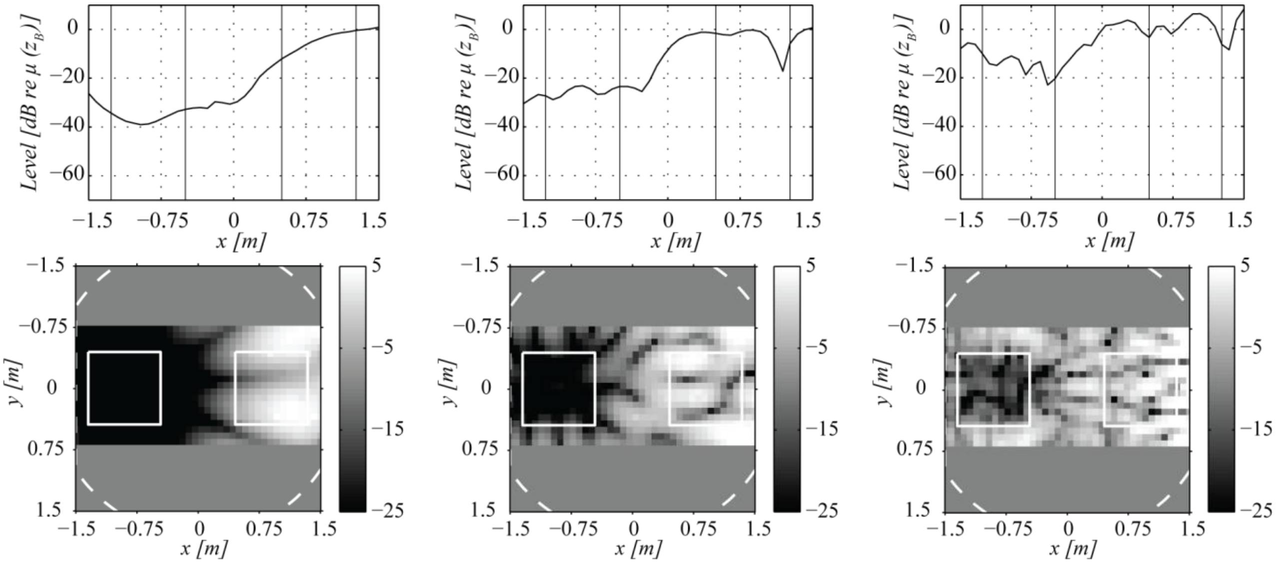


Figure 6. Experimental results obtained with contrast optimisation for zones with a side length of 0.9 m. Top row, sound pressure level along a line through the two zones (indicated by vertical lines); bottom row, sound pressure level. Left column, 0.25 kHz; middle column, 0.5 kHz; right column, 1 kHz.

3.2 Sound field synthesis

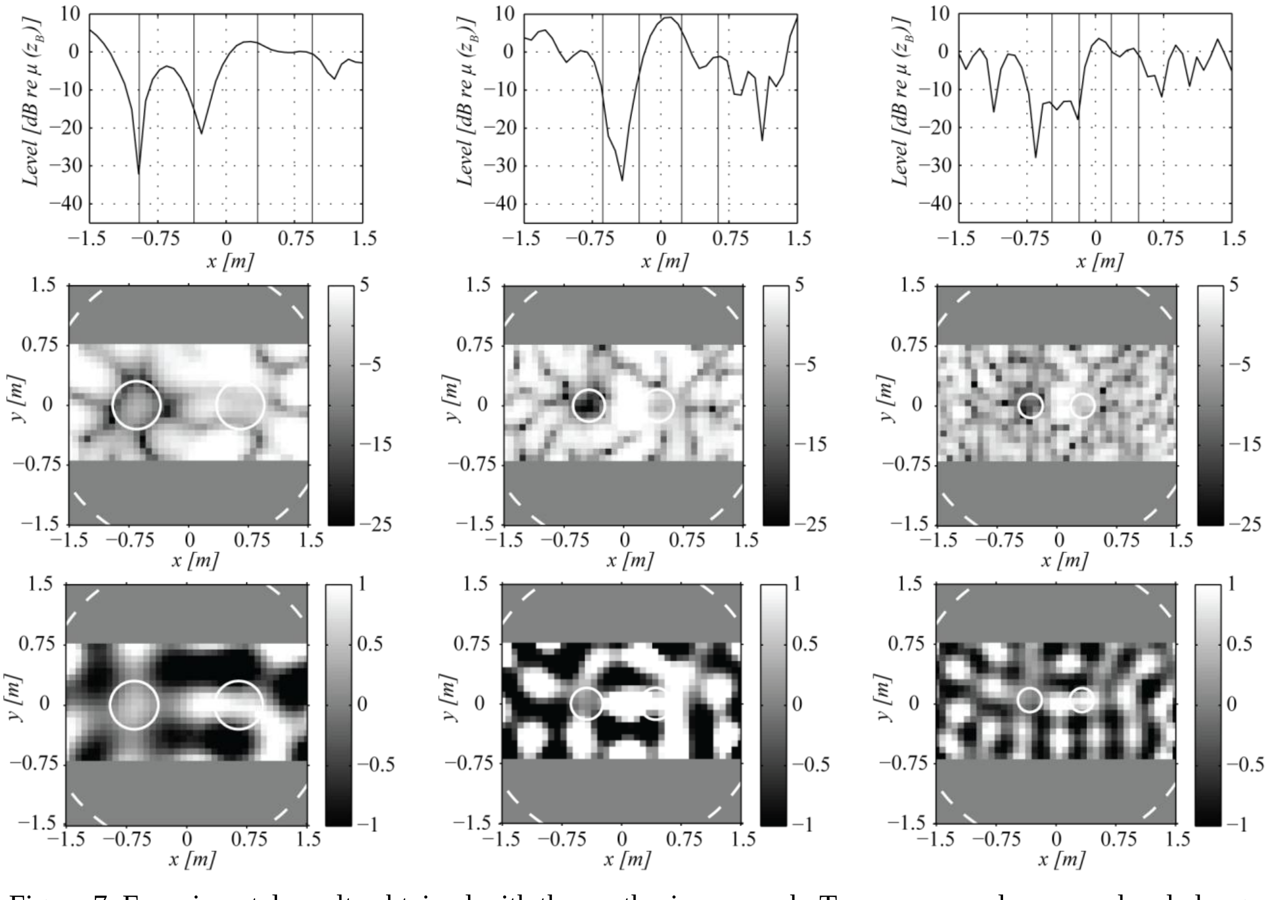


Figure 7. Experimental results obtained with the synthesis approach. Top row, sound pressure level along a line through the two zones (indicated by vertical lines); middle row, sound pressure level; bottom row: real part of complex pressure. Left column, 400 Hz and zone radius of 0.3 m; middle column, 600 Hz and zone radius of 0.2 m; right column, 800 Hz and zone radius of 0.15 m.

Some experimental results obtained with the synthesis approach are shown in Fig. 7. It can be seen that the controlled zones are very small – so small that it is difficult to see the propagating wavefronts in the plots of the real part of the complex pressure. However, the small zones are an inevitable consequence of the limited number of control sources. The obtained level differences are acceptable but less than predicted, undoubtedly because the room is not anechoic.

3.3 Two sound programmes

Finally Fig. 8 shows the results of an attempt to drive two zones with two different pure tones. As can be seen fairly good signal-to-noise ratios are achieved.

Figure 8. Sound pressure level of two different pure tones along a line through two zones (indicated by vertical lines). Left, contrast optimisation, 252 and 500 Hz; right, the synthesis approach, 600 and 800 Hz.

4. Discussion

It is a clear advantage of the sound field synthesis approach that it offers detailed control of the sound field in the zones, not just the sound pressure level; for example, plane waves can be synthesised in the controlled regions. By contrast, the optimisation approach considers only the ratio of potential energies in the zones, and there is no control of the phase or direction of propagation of the resulting sound field. This may well give rise to disturbing perceptual artefacts. On the other hand, the synthesis approach requires a relatively large number of control sources, whereas the optimisation approach works well with a much lower number of sources and there are no specific requirement to the array geometry.

The optimisation approach inherently compensates for reflections from the boundaries of the room provided that all transfer functions to the zones are known. On the other hand, the synthesis approach relies on a description of the sound field in terms of spherical harmonics; therefore significant reflections from the boundaries must be described through such expansions.

5. Conclusions

Two techniques for realisation of sound zones have been investigated: the contrast optimisation approach and the sound field synthesis approach. The former optimises the difference in sound pressure level between bright and dark regions, and the latter synthesises a desired sound field in a region and can, for instance, suppress sound in another region. The two techniques have been examined through a simulation study with point sources under free field conditions. The contrast optimisation method has also been examined with reflections from room boundaries taken into account.

The sound field synthesis approach offers detailed control of the sound field, not just the sound pressure level, but requires an inordinate number of control sources; otherwise the controlled zones are very small. By contrast, the optimisation approach considers only the distribution of potential energy in the zones, and there is no control of the phase or direction of propagation of the resulting sound field, but it works well with a much lower number of sources. The uncontrolled direction of propagation can be expected to vary erratically with frequency.

Both methods have been validated through an extensive series of measurements in a heavily damped listening room provided with a circular loudspeaker array of sixteen channels. With the optimisation approach it was possible to generate two zones each of about 0.8 m^2 placed 1.8 m apart with the average sound pressure level in the dark zone reduced by between 10 and 34 dB at frequencies between 100 Hz and 1.5 kHz; and it was also possible to generate different signals in the two controlled zones with a signal-to-noise ratio of about 35 dB.

With ‘only’ sixteen loudspeakers the controlled regions for the synthesis approach were small, as predicted. However, the experimental results confirm that it is possible to generate a zone with a plane wave and a quiet zone simultaneously and agree with the predictions. Generating two sound zones with different signals simultaneously resulted in signal-to-noise ratios between 12 and 21 dB.

REFERENCES

1. S.J. Elliott and P.A. Nelson, ‘Multiple-point equalization in a room using adaptive digital filters,’ *J. Audio Eng. Soc.* **37**, 899–907 (1989).
2. J.-W. Choi and Y.-H. Kim, ‘Generation of an acoustically bright zone with an illuminated region using multiple sources,’ *J. Acoust. Soc. Am.* **111**, 1695-1700 (2002).
3. M. Jones and S. Elliott, ‘Active headrest for personal audio, *J. Acoust. Soc. Am.* **119**, 2702-2709 (2006).
4. M. Shin, S.Q. Lee, F.M. Fazi, P.A. Nelson, D. Kim, S. Wang, K.H. Park, and J. Seo, ‘Maximization of acoustic energy difference between two spaces. *J. Acoust. Soc. Am.* **128**, 121-131 (2010).
5. A.D. Belegundu and T.R. Chandrupatle, *Optimization Concepts and Applications in Engineering*,’ Prentice Hall, Englewood Cliffs (1999).
6. M. Camras, ‘Approach to recreating a sound field,’ *J. Acoust. Soc. Am.* **43**, 1425–1431 (1968).
7. O. Kirkeby and P.A. Nelson, ‘Reproduction of plane wave sound fields,’ *J. Acoust. Soc. Am.* **94**, 2992-3000 (1993).
8. J.-H. Chang, J.-W. Choi and Y.-H. Kim, ‘A plane wave generation method by wave number domain focusing,’ *J. Acoust. Soc. Am.* **128**, 2758-2767 (2010).
9. A.O. Santillán, ‘Spatially extended sound equalization in rectangular rooms,’ *J. Acoust. Soc. Am.* **110**, 1989-1997 (2001).
10. M.A. Gerzon, ‘Periphony – width-height sound reproduction,’ *J. Audio Eng. Soc.* **21**, 2-10 (1973).
11. D.G. Malham and A. Myatt, ‘3-D sound spatialization using ambisonic techniques,’ *Comp. Music J.* **19**, 58-70 (1995).
12. A.J. Berkhout, D. de Vries and P. Vogel, ‘Acoustic control by wave field synthesis,’ *J. Acoust. Soc. Am.* **93**, 2764-2778 (1993).
13. J. Ahrens and S. Spors, ‘An analytical approach to sound field reproduction using circular and spherical loudspeaker distributions,’ *Acta Acust. un. with Acust.* **94**, 988-999 (2008).
14. Y.J. Wu and T.D. Abhayapala, ‘Spatial multizone soundfield reproduction,’ *Proc. IEEE Intern. Conf. Acoust., Speech & Signal Proc. (ICASSP)*, pp. 93-96, Tapei, Taiwan (2009).
15. T. Betlehem and T.D. Abhayapala, ‘Theory and design of sound field reproduction in reverberant rooms,’ *J. Acoust. Soc. Am.* **117**, 2100–2111 (2005).
16. M. Olsen and M. Møller, ‘Sound zones,’ MSc thesis, Technical University of Denmark (March 2011).
17. E.G. Williams, *Fourier Acoustics. Sound Radiation and Nearfield Acoustical Holography*, Academic Press, San Diego (1999).
18. B.U. Felderhof and R.B. Jones, ‘Addition theorems for spherical wave solutions of the vector Helmholtz equation,’ *J. Math. Physics* **28**, 988-999 (1987).
19. A. Messiah, *Quantum Mechanics* **II**, pp. 1054-1056, North-Holland Publishing Company, Amsterdam (1962).
20. R. Dmowska and B. Saltzman, *Advances in Geophysics* **36**, pp. 100-101, Academic Press, San Diego (1994).
21. M.A. Gumerov and R. Duraiswami, ‘Recursions for computation of multipole translation and rotation coefficients for the 3D Helmhotz equation,’ *SIAM J. Sci. Comput.* **25**, 1344-1381 (2003).
22. Y.J. Wu and T.D. Abhayapala, ‘Theory and design of soundfield reproduction using continuous loudspeaker concept,’ *IEEE Trans. Speech, Audio & Lang. Proc.* **17**, 107-116 (2009).
23. D.B. Ward and T.D. Abhayapala, ‘Reproduction of a plane-wave sound field using an array of loudspeakers.’ *IEEE Trans. Speech & Audio Proc.* **9**, 697–707 (2001).
24. S. Favrot and J.M. Buchholz, ‘LoRA: A loudspeaker-based room auralization system,’ *Acta Acust. un. with Acust.* **96**, 364-375 (2010).