MITIGATION OF NONLINEAR DISTORTION IN SOUND ZONE CONTROL BY CONSTRAINING INDIVIDUAL LOUDSPEAKER DRIVER AMPLITUDES

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ABSTRACT

Loudspeaker drivers are subject to nonlinear distortion in the low frequency range at high input levels. In sound zone control, distortion not only reduces the acoustic contrast between zones, but also gives perceived artefacts. Standard sound zone methods, such as acoustic contrast control, apply a constraint to the overall input power, but individual loudspeaker drivers are not controlled and the nonlinear distortion is mainly produced by the loudspeaker drivers with the highest input power. We investigate a sound zone control algorithm where amplitude limits are applied on a per-loudspeaker-driver basis, and its effect on the mitigation of nonlinear distortion. Experiments with pure-tone signals show that this approach improves the contrast for the pure tone component by 7.6 dB. Second order harmonic distortion in the dark zone is suppressed by 8.4 dB and third order harmonic distortion by 4.4 dB, compared to acoustic contrast control.

***Index Terms*—** Sound zones, nonlinear distortion, individual amplitude constrained acoustic contrast control.

1. INTRODUCTION

A personal sound zone system creates multiple listening zones within a shared space without physical barriers by superposition of sounds played by multiple loudspeakers or loudspeaker arrays [1]. Each zone can be silent or play a given audio content with minimal interference to other zones. Constructive and destructive interference is obtained by modifying the signal played in each loudspeaker driver with a filter designed using a particular control method. Zones where sound is audible are referred to as bright, while silent zones are referred to as dark.

Control strategies with different optimization targets have been proposed. Mode matching evaluates the desired sound field at a single point by expressing the sound field as a linear combination of basis functions [2, 3]; wave field synthesis reconstructs a sound field based on the Kirchhoff-Helmholtz integral [4, 5, 6], which is suitable for multiple listeners in a broad area. Alternatively, sound zones can be created by

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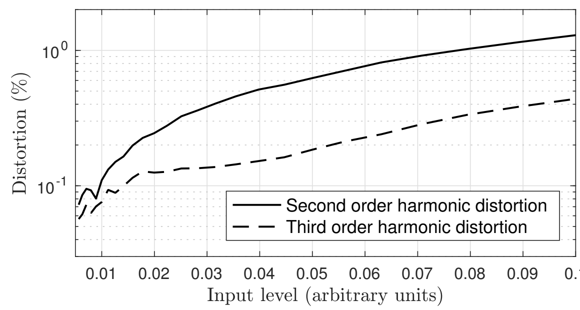

Fig. 1. Harmonic distortion as a function of input level for a pure-tone signal at 250 Hz. The input level 0.01 generates a sound pressure level of 63 dB on-axis at a distance of 1 m from the loudspeaker driver.

optimizing the pressure or energy distribution across zones, such as pressure matching [7, 8, 9], acoustic contrast control [10, 11, 12, 13, 14] and planarity control [15, 16, 17]. In these methods, the zones are defined by distributed microphones sampling the sound field.

Pressure matching minimizes the least square error between the target sound field and the reproduced sound field [7]. Pressure matching has the advantage of accurate amplitude and phase reproduction below the spatial aliasing frequency, but at a price of a high control effort [17]. Above the aliasing frequency, the performance is reduced [15]. Acoustic contrast control (ACC) is designed to maximize the energy ratio between the bright and dark zones [10]. Research on ACC has been focused on e.g. improving robustness through regularisation [11] and minimizing the sensitivity to noise [14]. Individual regularisation has been used to penalize the control effort for protection of drivers in a sound zone system [18]. The cost function of ACC does not consider phase information, therefore the sound field in the bright zone can appear to have multiple directions of arrival giving a confusing listening experience. To overcome this drawback, planarity control adds an additional constraint on the energy flowing direction in the bright zone [15, 16, 17].

Sound zone control methods assume that loudspeaker drivers behave linearly. In reality, loudspeaker drivers are subject to nonlinear distortion. Nonlinear distortion is pro-

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nounced in the low frequency range and at high input levels. An example of the increase of second and third order distortion with input level for a 250 Hz pure tone signal in a SB-Acoustics SB65WBAC25-4 driver is shown in Fig. 1.

In recent papers, the authors investigated the impact of harmonic distortion on sound zones designed using acoustic contrast control and planarity control [19, 20]. Simulations and experiments were conducted with pure tone signals and revealed that harmonic distortion contributes to contrast loss and is clearly audible in the dark zone. It was also shown that nonlinear distortion can be partially compensated through regularisation. Regularisation penalizes control effort and in turn nonlinear distortion. However, the penalty is on the overall control effort and therefore some loudspeaker drivers can play much louder than others and generate considerable amounts of nonlinear distortion.

Figure 2 shows spectra obtained from two individual loudspeaker drivers in an ACC sound zone experiment using a pure tone f = 250 Hz input signal. Figure 2(a,c) are spectra recorded in the zones due to the driver with minimum input level, while Fig. 2(b,d) are spectra due to the driver with maximum input level. It is evident that the driver playing loudest generates a significantly larger amount of nonlinear distortion and the contrast between zones deteriorates, even though the overall input power is at a reasonable level.

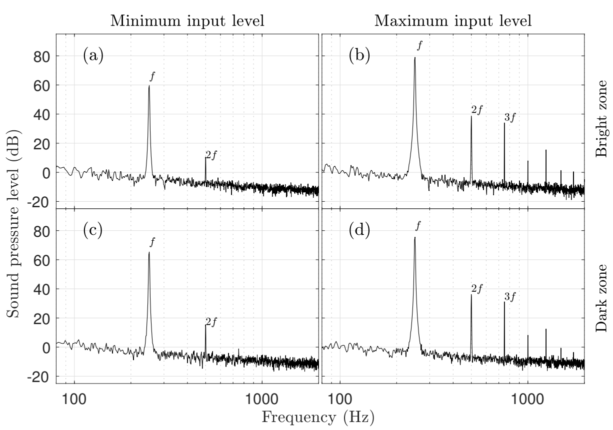

Fig. 2. Measured spectra in the bright zone (a,b) and dark zone (c,d) for drivers having the minimum (a,c) and maximum (b,d) input level.

Based on these observations it is interesting and potentially beneficial to limit the control effort on a per-loudspeaker-driver basis, so that each channel will only generate nonlinear distortion within an acceptable amount, e.g. 1 %. We present the results from an experimental investigation of mitigation of nonlinear distortion using individual-amplitude constrained ACC and a pure tone 250 Hz input signal. A pure tone input signal is chosen as it makes the interpretation of nonlinear distortion unambiguous. Experiments were conducted in an anechoic room to make room acoustic effects negligible.

2. ACOUSTIC CONTRAST CONTROL

Acoustic contrast control aims at maximizing the energy ratio between the bright and dark zones [11]. Each zone is defined by an array of N_B or N_D microphones, where subscript B denotes the bright zone, and D denotes the dark zone. Each microphone measures the sound pressure as p_i, $i = 1, \ldots, N_B(N_D)$, therefore, the sound pressure in the zones are denoted as

$$\boldsymbol{p}_B = [p_1 \ldots p_{N_B}]^T, \quad \boldsymbol{p}_D = [p_1 \ldots p_{N_D}]^T. \tag{1}$$

Assume the sound zones are created by an array of L loudspeaker drivers driven by complex signals

$$\boldsymbol{q} = [q_1 \ldots q_L]^T, \tag{2}$$

where element q_k is the driving signal for channel k, $k = 1, \ldots, L$. Sound pressure in the zones can be written as

$$\boldsymbol{p}_B = G_B\boldsymbol{q}, \quad \boldsymbol{p}_D = G_D\boldsymbol{q}, \tag{3}$$

where G_B and G_D are transfer functions from loudspeaker inputs to microphone measurements.

The acoustic contrast is defined as the averaged energy ratio between the bright and dark zones. For the sake of loudspeaker driver protection or volume control, the input electrical power or control effort should be constrained, i.e.

$$\boldsymbol{q}^H\boldsymbol{q} \leq E, \tag{4}$$

where E is the constraint on control effort. Applying the Lagrange multipliers optimization method, the cost function is formulated as

$$\begin{aligned} J_{SACC} =& \boldsymbol{q}^H G_D^H G_D \boldsymbol{q} + \lambda_B \left(\boldsymbol{q}^H G_B^H G_B \boldsymbol{q} - B\right) \\ &+ \lambda_E \left(\boldsymbol{q}^H \boldsymbol{q} - E\right), \end{aligned} \tag{5}$$

where λ_B and λ_E are Lagrange multipliers, B is the target acoustic energy in the bright zone. When solving the optimization problem, $\boldsymbol{q}$ can be properly scaled so that the acoustic energy in the bright zone achieves B, thus the second term is zero and λ_B can be neglected. In this paper, sound zone control based on Eq. (5) will be referred to as *standard acoustic contrast control* (SACC).

For better power control, a modified cost function with individual regularisation terms for each loudspeaker driver is proposed. As nonlinear distortion is amplitude dependent, it is desirable to set an amplitude threshold e for each loudspeaker driver, below which the generated nonlinear distortion is considered acceptable,

$$|q_k| \leq e, \quad k = 1, \ldots, L. \tag{6}$$

By using the Lagrange multipliers optimization method, the cost function is formulated as

$$\begin{aligned} J_{IACC} =& \boldsymbol{q}^H G_D^H G_D \boldsymbol{q} + \lambda_B \left(\boldsymbol{q}^H G_B^H G_B \boldsymbol{q} - B\right) \\ &+ \sum_{k=1}^{L} \lambda_k \left(|q_k| - e\right), \end{aligned} \tag{7}$$

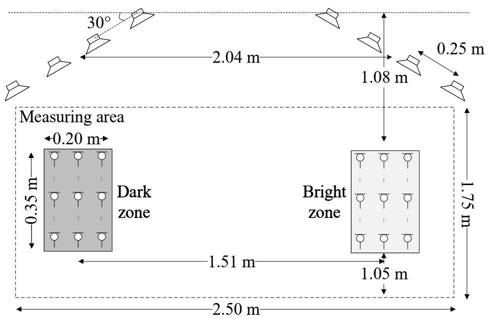

Fig. 3. Experimental setup in an anechoic room.

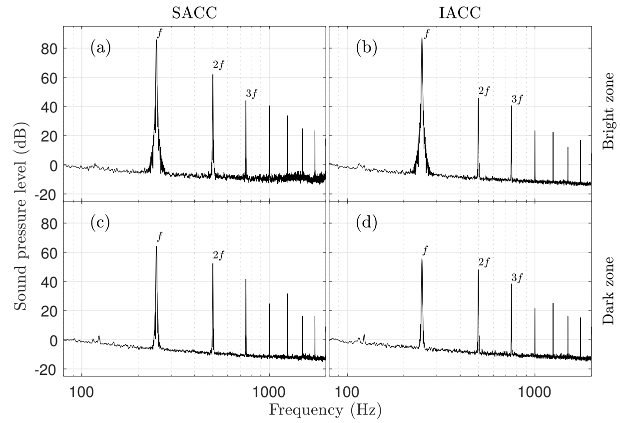

Fig. 4. Measured spectra for SACC (a,c) and IACC (b,d). (a,b) are spectra for the bright zone; (c,d) are spectra for the dark zone.

where λ_k ($k = 1, \ldots, L$) are Lagrange multipliers penalising the input amplitude for each channel. To determine the appropriate λ_k values, an iterative approach is adopted:

1. Determine a per-channel amplitude threshold e, below which the nonlinear distortion is acceptable.
2. Initialize the Lagrange multipliers λ_k, $k = 1, \ldots, L$ with relative small values, e.g. 10^{-5}.
3. Calculate vector $\boldsymbol{q}$, and find channels $i_{1,2,\ldots,n}, n \leq L$ where $|q_{i_{1,2\cdots,n}}| > e$.
4. Scale the Lagrange multipliers for channels $i_{1,2,\cdots,n}$, $\lambda_{i_{1,2,\cdots,n}} = \delta\lambda_{i_{1,2,\cdots,n}}$, where $\delta > 1$.
5. Recalculate the vector $\boldsymbol{q}$, if the amplitudes of all channels are smaller than e, stop. Otherwise, go back to 3.

By this approach, all loudspeaker drivers will play at levels giving acceptable amounts of nonlinear distortion. We refer to this modified ACC as *individual-amplitude-constrained acoustic contrast control* (IACC).

3. EXPERIMENTAL MEASUREMENTS

Measurements were performed in an anechoic chamber of dimension $4 \times 4 \times 4$ m^3 with the layout shown in Fig. 3. Four equally spaced 2.5" full-range drivers (SB-Acoustics SB65WBAC25-4) are installed in each loudspeaker array. Two microphone arrays in 3×8 layouts of dimensions 20 cm $\times$ 35 cm are placed in the bright and dark zone respectively, and are used to measure transfer functions and sound pressure levels. The sound pressure maps shown in Fig. 5 are measured by assembling all microphones into one 48 microphone array and moving this array to sample the area bordered by the dashed line in Fig. 3 [19].

All measurements are conducted with a 250 Hz pure tone input signal, which can excite reasonable amounts of nonlinear distortion, Fig. 2. For measurements using SACC, λ_E is set to be 10^{-2}, giving an optimum balance between acoustic contrast and nonlinear distortion [19]. For measurements using IACC, the amplitude threshold is $e = 0.08$, corresponding to a maximum of 1% of second order harmonic distortion. The target sound pressure level (SPL) in the bright zone is 88 dB for both SACC and IACC.

Spectra from bright and dark zones created with either SACC or IACC and power averaged over all 24 microphones are shown in Fig. 4. In the bright zone, the 250 Hz fundamental component has compariable amplitudes with either method, 84.7 dB for SACC and 85.6 dB for IACC. It is remarkable that in the dark zone, the SPL of the fundamental component is 6.7 dB smaller with IACC than with SACC, i.e. the contrast is improved. This is due to the amplitude constraint on each loudspeaker driver, which reduces not only harmonic distortion but also reduces nonlinear distortion of the fundamental component. Both the bright and dark zone created with SACC has higher harmonic distortion than when IACC is used. As an example, the second order harmonic component in the bright zone is 60.9 dB with SACC and only 45.8 dB with IACC. In the dark zone, the second order harmonic distortion is found to be improved by 8.4 dB with IACC.

Maps of SPL distributions are shown in Fig. 5 for SACC (top row) and IACC (bottom row). Broadband measurements integrated over all frequency components and background noise are given in Fig. 5(a,e). The presence of bright and dark zones are evident with both methods, the broadband acoustic contrast is 22.9 dB for SACC, and improves to 30.5 dB with IACC. The subsequent columns of Fig. 5 show frequency resolved maps of the components at 250 Hz, 500 Hz and 750 Hz. For the 250 Hz fundamental component there is a contrast of 23.3 dB for SACC which improves to 30.9 dB with IACC. The maps for the second order harmonic component reveal that the bright zone SPL is 60.9 dB with SACC, and 45.8 dB for IACC, i.e. 15.1 dB lower. Similar results are obtained in the dark zone, where IACC gives an 8.4 dB lower

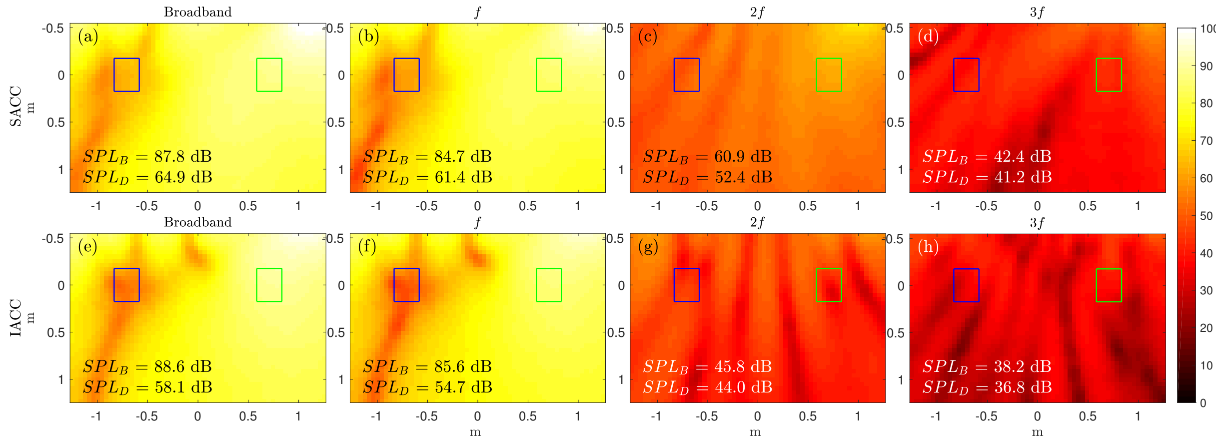

Fig. 5. Broadband and frequency-resolved SPL maps for SACC (top row) and IACC (bottom row).

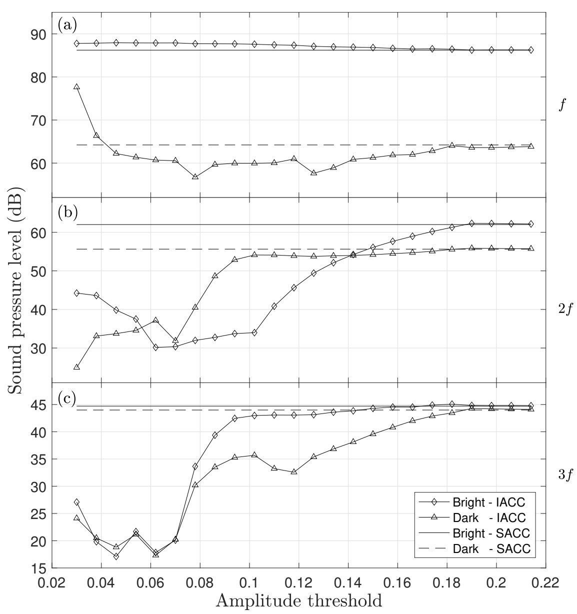

Fig. 6. Frequency resolved SPLs for a range of amplitude threshold using IACC. For comparison purpose, the results of SACC are given as straight lines: solid-line for the bright zone; dashed-line for the dark zone. (a) gives results for the fundamental component; (b) for the second order harmonic component; (c) for the third order harmonic component.

SPL than SACC. The improved behaviour is also observed for the third order harmonic component, where IACC results are ∼4 dB better than SACC results in both zones.

IACC experiments using a range of amplitude thresholds have been performed and compared with SACC, Fig. 6. For the fundamental component the bright zone created by IACC has higher SPL compared to SACC when the amplitude threshold is below 0.17, Fig. 6(a). This is due to loudspeaker drivers controlled by IACC playing at lower levels than SACC, causing less nonlinear distortion on the fundamental component. In the dark zone, SPL for IACC is lower than SACC when the amplitude threshold is in the range of 0.04 to 0.17. Below 0.04, the IACC method does not have enough energy to create high acoustic contrast. If the amplitude threshold is below 0.03, IACC can not even create the target SPL in the bright zone. When the amplitude threshold is above 0.17, the constraints are not active, and IACC is effectively equivalent to SACC. Between these two thresholds, IACC is able to re-distribute the energy across different loudspeaker drivers creating high acoustic contrast, while keeping the nonlinear distortion at low levels. For the second order harmonic component, Fig. 6(b), the SPLs for both bright and dark zones created by IACC are lower than SACC, when the amplitude threshold is below 0.17; above this limit IACC is identical to SACC, as results for the fundamental component. Similar observations are found for the third order harmonic component, see Fig. 6(c).

4. CONCLUSION

Mitigation of nonlinear distortion artefacts in sound zone control has been experimentally studied through individual-amplitude-constrained acoustic contrast control. Nonlinear distortion depends on the input amplitude; higher input amplitude leads to higher nonlinear distortion. With IACC, the amplitude for each loudspeaker driver is constrained to allow for a certain amount of nonlinear distortion; the algorithm re-distributes the control effort to create high acoustic contrast while keeping the nonlinear distortion at low levels. Experimental results show that the acoustic contrast for the fundamental component is improved, and the harmonic distortion is reduced. It is also noticeable that the amplitude threshold cannot be arbitrarily small, as the input power will not be enough to create the target SPL in the bright zone in the first place.

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