# Individualized low-frequency response manipulation for multiple listeners using chameleon subwoofer arrays

Adam J. Hill and Malcolm O. J. Hawksford
Audio Research Laboratory
School of Computer Science & Electronic Engineering, University of Essex
Colchester, United Kingdom
ajhilla@essex.ac.uk mjh@essex.ac.uk

*Abstract*— **Low-frequency acoustical responses are naturally position dependent across wide listening areas. This is predominantly due to room modes in small, closed spaces. Numerous methodologies have been proposed targeting room mode compensation to give an objectively even response across all listening locations. These techniques cannot guarantee, however, that every listener receives an equally pleasing subjective response. Chameleon subwoofer arrays (CSA) were originally developed to minimize low-frequency spatiotemporal variations by addressing frequency response errors at multiple listening locations using a subwoofer system consisting of multiple degrees of freedom. The CSA system can alternatively be utilized to control listening locations independently, allowing each listener to adjust their localized low-frequency response to their liking. This alternate CSA implementation is evaluated using a bespoke finite-difference time-domain (FDTD) algorithm for small home theater applications.**

***Keywords-audio signal processing, loudspeakers, subwoofers, frequency-domain analysis, finite-difference time-domain modeling***

## I. INTRODUCTION

Numerous methodologies exist for low-frequency control over a wide listening area. The vast majority, if not all, of these techniques aim to either deliver an objectively even frequency response at all listening areas or to optimize the response at a single location. Few of these systems consider the influence of listener subjectivity which can vary considerably over even a small group of people. A system that allows each user to independently tailor the low-frequency response to suit their preferences without affecting other listening areas would be able to compensate for subjective differences, thus providing all users with an enjoyable listening experience.

Chameleon subwoofer arrays (CSA) were initially developed following the same line of reasoning as existing low-frequency correction systems: to provide an even response at all listening locations. The multiple degrees of freedom available within the CSA structure allows for each target location to be individually controlled, permitting multiple distinct frequency responses to exist in space simultaneously.

This paper explores the feasibility of this approach using finite-difference time-domain (FDTD) acoustical simulation software [1]. This investigation will be preceded by an overview of room acoustics, focusing on factors resulting in spatio-pressure variations, followed by a description of the CSA low-frequency room correction technique.

## II. ROOM ACOUSTICS OVERVIEW

A sound wave generally travels a distance of twenty to thirty times the largest dimension of a room before falling 60 dB below its initial sound pressure level [2]. This is referred to as the reverberation time of the room. The large amount of reflections gives rise to standing waves which occur when the half-wavelength of a frequency is an integer multiple of one or more combination of parallel surfaces [3]. The frequencies at which these standing waves occur are referred to as room modes, which contribute significantly to the noticeable effect of the room on a sound reproduction system's response.

Theoretical room mode frequencies can be calculated for rectangular rooms using (1) [3]. Of course, room modes exist in all closed spaces, although non-rectangular modal distributions are much more difficult to predict.

$$f_m = \frac{c}{2}\sqrt{\left(\frac{\eta_x}{L_x}\right)^2 + \left(\frac{\eta_y}{L_y}\right)^2 + \left(\frac{\eta_z}{L_z}\right)^2} \tag{1}$$

where the modal frequency, $f_m$, with indices, ($\eta_x$, $\eta_y$, $\eta_z$), is defined by the speed of sound, $c$, and the room length, width and height ($L_x$, $L_y$, $L_z$, respectively).

The issue encountered with room modes is that the sound pressure level for a listener is largely dependent on the listener's location within the standing wave pattern. This can result in perceived differences between adjacent listeners.

A common metric used to classify these perceived differences is called spatial variance. Spatial variance is calculated at each frequency bin over multiple listening locations. The frequency bin spatial variances are then averaged, giving the spatial variance over all listening locations and frequency bins (2) [4].

$$SV = \frac{1}{N_f}\sum_{i=f_{lo}}^{f_{hi}}\sqrt{\frac{1}{N_p - 1}\left(L_p(p,i) - \overline{L_p(i)}\right)^2} \tag{2}$$

where spatial variance, $SV$, is calculated over the frequency range $f_{lo}$ to $f_{hi}$, consisting of $N_f$ frequency bins at $N_p$ listening locations. $L_p(p, i)$ represents the measured sound pressure level at location, $p$, at the $i^{th}$ frequency bin, while $\overline{L_p(i)}$ is the mean sound pressure level over all listening locations.

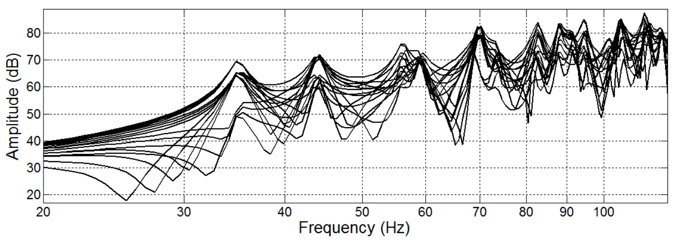


Figure 1. Simulated frequency responses over a 16-point listening grid (without correction)

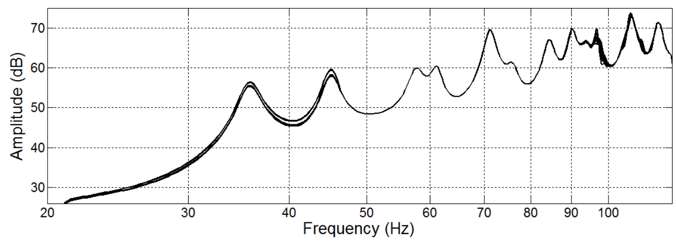


Figure 2. Simulated frequency responses over a 16-point listening grid (with CSA correction)

As an example a 5m x 4m x 3m rectangular room was modeled with a single omnidirectional subwoofer placed at a room corner. A sixteen point listener grid was arranged in the room, with its center at (2.4m, 1.8m, 1.8m), and the frequency response at each location (Fig. 1) was determined using a maximum length sequence (MLS) [5].

The results in Fig. 1 exhibit a spatial variance of 5.5764 dB which indicates significant frequency response discrepancies from point to point in the room. A system configuration of this sort clearly is not capable of delivering similar low-frequency responses to multiple listeners within a room.

## III. CHAMELEON SUBWOOFER ARRAYS

Commercially available subwoofers generally contain a single drive unit, giving an omnidirectional polar pattern. Systems employing these units have little flexibility in terms of low-frequency control due to the single degree of freedom for each subwoofer. Chameleon subwoofer arrays (CSA) were developed to increase the degrees of freedom in each unit, thus providing greater low-frequency response control. CSAs were motivated by the work in [6] and are described in detail in [7].

A CSA consists of one or more multi-drive unit subwoofer, where each unit consists of four orthogonally controlled spherical harmonic source components (one omnidirectional and three dipolar). Each source component within the system is activated separately and the impulse response at each listening location due to that component is measured. These measurements are used along with a target frequency response to generate a set of correction filters (3).

$$H = X^{-1}Y \tag{3}$$

where $H$ is a matrix containing the complex correction filter coefficients, $X$ is a matrix of the measured frequency responses and $Y$ is a matrix with the target frequency responses. Several stability considerations are applied to the resulting filter sets, including splitting the correction band to avoid overloading the dipolar units at very low frequencies where they are highly-inefficient [8] and limiting the upper correciton limit based on the Schroeder frequency [9].The default target response is the average room response in order to maintain the character of the natural room acoustics. This endows CSAs their “chameleon” descriptor, since the system can adapt to the natural acousical surroundings.

To demonstrate the capabilities of CSA technology, a space identical to that utilized for the simulations shown in Fig. 1 was reconfigured by replacing the single subwoofer with four multi-driver units at each room corner. This configuration provides sixteen degrees of freedom towards low-frequency control, dictating a maximum of sixteen target listening locations. The CSA was corrected using the average room response (Fig. 2).

The corrected system exhibits a spatial variance of 0.2076 dB, a 96.3% reduction from the uncorrected system. This illustrates the potential power of CSA correction. This system would deliver an approximately even low-frequency response to all listeners, unlike the uncorrected system where the responses are clearly position-dependent.

## IV. INDIVIDUALIZED RESPONSE MANIPULATION

An objectively even low-frequency response across a listening area is a considerable improvement over the variations encountered using an uncorrected system. Current technology, however, cannot control a person’s subjective interpretation of sound; therefore a robust low-frequency correction system should provide users control over the reproduced sound’s spectral characteristics at their unique location.

CSAs allow for individual control of the target response at each measurement point; something which has not been investigated to date, although previous work has split target points into two distinct correction areas for use in sound reinforcement. This scenario requires minimal low-frequency energy on a stage while simultaneously providing even coverage across an audience area [10].

The aim of this particular work, therefore, is to allow for frequency response control at each listener location. The multi-band CSA correction procedure lends only the higher frequency band (~ 40 – 120 Hz) for individual correction, as the lower band (below 40 Hz) utilizes only the omnidirectional components, reducing the number of target points by a factor of four. Fortunately, most home theater systems are in rooms where only the lowest room mode falls below 40 Hz, resulting in room pressurization in that range with low spatial variance.

An identical configuration as that used to demonstrate the even frequency response correction (Fig. 2) was utilized to highlight individualized frequency response manipulation. Ideally, altering the response at one location will have no effect on other points. As an example, the resonance at 71 Hz can be attenuated for a single location (Fig. 3).

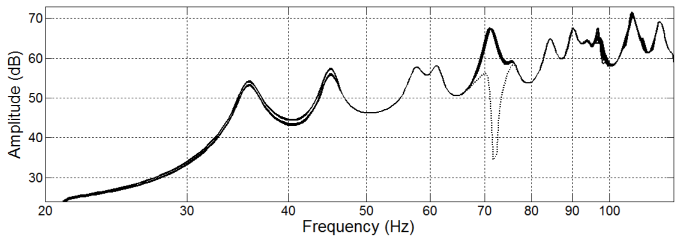


Figure 3. Simulated frequency responses over a 16-point listening grid (dotted line = 71 Hz attenuation at single listening point)

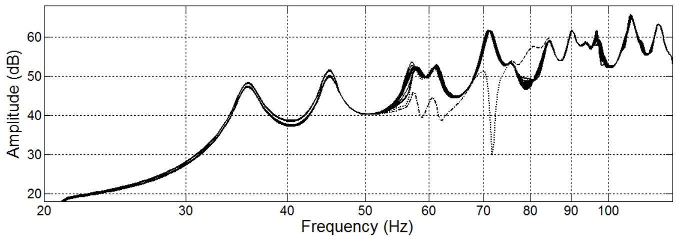


Figure 4. Simulated frequency responses over a 16-point listening grid (dotted line = 71 Hz attenuation, dashed line = 80 Hz boost, dash-doted line = 59 Hz attenuation)

The single-location manipulation has no noticeable effect on any other point in the listening area, although system output has reduced by approximately 2 dB due to the added requirements on the correction filters. Another two listening locations can be adjusted to give a 9 dB boost centered at 80 Hz and a 9 dB cut centered at 59 Hz (Fig. 4).

The additional adjustment shows the boost and cut at the target locations with only slight (< 1 dB) changes at other points over those frequency bands. The added requirements on the correction filters cause the system output to drop 4 dB. It can be deduced that for every target point attempting to deviate from the measured room average target response, there will be approximately 2 dB loss in output. This issue calls for a sound reproduction system to have sufficient headroom to compensate for this reduction.

These examples highlight the potential of CSAs for not only even listening area coverage, but also for individual control where multiple independent low-frequency sound fields can simultaneously exist in a relatively small area. With the ever-increasing popularity of smart-phones, the authors can envision a sound reproduction system whereby listeners can connect wirelessly to the system with a mobile application and then adjust the low-frequency response in their area in real-time. The real-time manipulation is made possible by the direct calculation approach of the CSA system (3), which could prove difficult using standard optimization algorithms.

## V. Conclusions

An alternative approach to CSA spatiotemporal low-frequency room correction has been introduced, demonstrating how the frequency response at each listening location can be individually controlled while maintaining nearly complete independence from other location responses. The effective frequency range of correction is limited by the higher operating band of the CSA, which is defined by the measurement point spacing on the low end and the Schroeder frequency on the high end. In the case studied in this work, this amounted to a controllable range from 40 – 120 Hz over sixteen listening locations.

System efficiency must be kept in mind when implementing a system of this sort, as a 2 dB drop in output sound pressure level was observed for each additional target location wishing to deviate from the average room response. A sound reproduction system with adequate headroom, however, should be able to handle this effect without much problem.

As all work pertaining to CSAs up to and including this paper has operated exclusively within a virtual environment, future work necessitates practical experimentation. At the writing of this paper, a CSA prototype has been constructed and tested for polar pattern control capabilities and is currently in the reconstruction phase to address various design issues.

Even so, simulated CSAs have given strong indication that they can be practically realized, which could prove extremely useful for sound reproduction systems for home theater, cinema, nightclubs, live sound and even art installation applications where both objective and subjective criteria can be met, giving all listeners and/or performers a pleasing listening experience.

## References


[1] Hill, A.J.; M.O.J. Hawksford. "Visualization and analysis tools for low frequency propagation in a generalized 3D acosutic space." 127th Convention of the Audio Engineering Society, paper 7901. October, 2009.

[2] Walker, R. "Low-frequency room responses: Part 1 – Background and qualitative considerations." BBC Research Department Report. RD 1992/8. 1992.

[3] Toole, F.E. *Sound Reproduction: Loudspeakers and Rooms*. Focal Press, Boston. 2008.

[4] Celestinos, A.; S. Birkedal Nielsen. "Optimizing placement and equalization of multiple low frequency loudspeakers in rooms." 119th Convention of the Audio Engineering Society, paper 6545. October, 2005.

[5] Kemp, J.A. "Theoretical and experimental study of wave propagation in brass musical instruments, Chapter 7 – Improvements to pulse reflectometry." Ph.D. Thesis, University of Edinburgh, UK. 2002.

[6] Howe, R.M.; M.O.J. Hawksford. "Methods of local room equalization and their effect over the listening area." 91st Convention of the Audio Engineering Society, paper 3138. October, 1991.

[7] Hill, A.J.; M.O.J. Hawksford. "Chameleon subwoofer arrays – Generalized theory of vectored sources in a closed acoustic space." 128th Convention of the Audio Engineering Society, paper 8074. May, 2010.

[8] Olson, H.F. "Gradient loudspeakers." Journal of the Audio Engineering Society, volume 21, issue 2, pp86-93. March, 1973.

[9] Schroeder, M.R.; K.H. Kuttruff. "On frequency response curves in rooms. Comparison of experimental, theoretical, and Monte Carlo results for the average frequency spacing between maxima." Journal of the Acoustical Society of America, volume 34, issue 1, pp76-80. January, 1962.

[10] Hill, A.J.; M.O.J. Hawksford. "Chameleon subwoofer arrays in live sound." Institute of Acoustics, Acoustics Bulletin, volume 36, number 3, pp32-40. May/June, 2011.