CHAMELEON SUBWOOFER ARRAYS IN LIVE SOUND

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1 INTRODUCTION

A high quality sound system should provide consistent coverage over the entire audience area while at the same time keep the sound pressure level (SPL) on stage to a minimum in order to provide musicians, technicians and production staff with a reasonable working environment. These requirements have predominantly been met with recent advancements in line array technology, where horizontal coverage patterns of 90° or 120° a re easily achievable, minimizing sound wraparound to the stage. Coverage patterns in the subwoofer operating range (generally below 100 Hz), however, are more difficult to control using simple one size fits all system configurations.

Historically, industry-standard subwoofers have operated as roughly omnidirectional sources, radiating energy equally in all directions. In recent years, a handful of companies have introduced cardioid or supercardioid pattern subwoofers which can help to limit low frequency energy on stage, depending on the system configuration. In addition to this, system technicians have long used the technique of rotating every other or every third subwoofer in vertical stacks 180° to achieve an approximate cardioid radiation pattern.

Conventional subwoofer systems suffer from a number of constraints, which can differ from venue to venue including placement issues, rigging capabilities, sightlines, truck space and, of course, budget. These drawbacks, which will be discussed in the following section, can severely diminish a system's capability to meet the low-frequency coverage and rejection criteria[1]. With this in mind, it is proposed that an adaptation of an emerging technique for small-room low-frequency control, termed chameleon subwoofer arrays[2] (CSA), can circumvent these practical issues and easily achieve venue-specific coverage patterns that should benefit both the audience and stage areas.

Conventional subwoofer system issues will be explored with relevant simulation results emphasizing key points, followed by a discussion on common techniques for low-frequency coverage pattern control. Next, chameleon subwoofer array correction theory will be presented in the context of small room applications and then the live sound adaption will be explained with emphasis on incorporating the system into existing industry-standard hardware. Simulations of large-scale concert venues utilizing this low-frequency control approach will be presented, highlighting the potential advantages of CSA technology in live sound.

2 CONVENTIONAL SUBWOOFER SYSTEM ISSUES

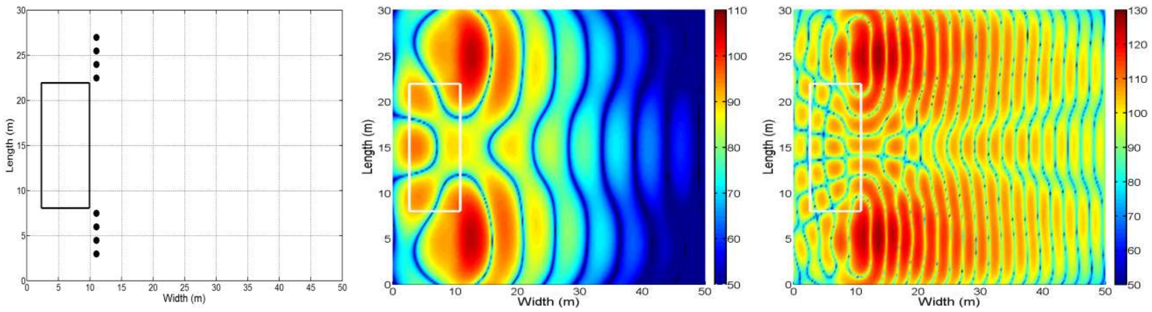
Units within a live sound subwoofer system can theoretically be placed and configured to achieve the desired coverage pattern. Unfortunately, there is a long list of constraints that usually prevent this, primarily stemming from production, venue and time restrictions; all of which will be discussed in the following sections.

2.1 Subwoofer placement

Disregarding production or venue constraints, simple subwoofer placement can be critical to define the overall coverage pattern. Depending on the spacing between each unit within the system a “power alley” (overly strong low-frequency energy down the center of the audience area) can emerge along with any combination of pressure nulls which travel outward from the stage. The individual unit spacing can also affect SPL on the stage. This is due to the constructive/destructive interference between the sound waves emitted from each source where location of any peaks/nulls depends of the intersection points of the individual sound waves.

To highlight this issue, a virtual outdoor venue was created with dimensions 50 m x 30 m x 10 m, where all surfaces except the ground plane and the stage were set as anechoic. Simulation of the stage has been shown to be critical for accurate results due to interfering reflections off the stage, corrupting the individual subwoofer directionality[1].

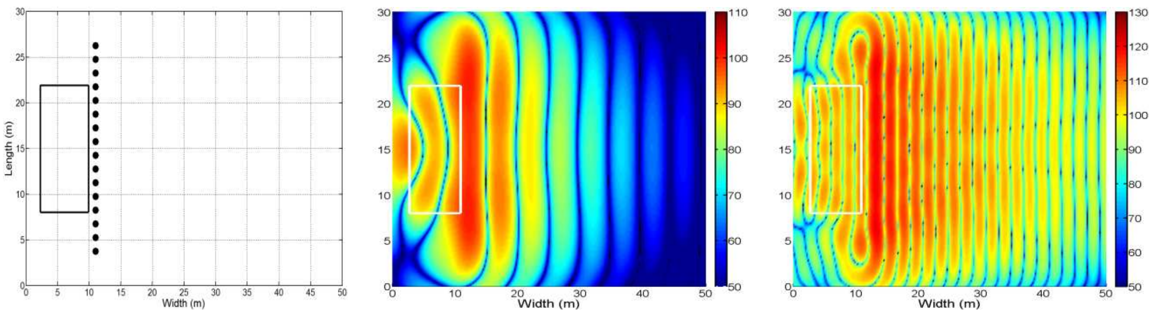
Sixteen cardioid subwoofers (with the cardioid pattern achieved following Olson’s work on gradient loudspeakers[3]) were initially placed in stacks of two in left/right clusters to simulate placement outside the stage corners, in line with the main PA. Sinusoidal test signals at 40 and 90 Hz were used to analyze the pressure distribution of the system (Figure 2.1).



(a) (b) (c)

Figure 2.1 16-unit cardioid left/right subwoofer system with system layout (a) and simulated coverage patterns at (b) 40 Hz and (c) 90 Hz

The left/right clusters give clear nulls within the central audience area as a result of destructive interference between the clusters. Also, stage rejection appears to suffer from the wide spacing causing a high stage SPL. Repositioning the units with equal spacing across the stage front can result in a significant reduction of the pressure nulls within the audience and also improve stage rejection (Figure 2.2).



(a) (b) (c)

Figure 2.2 16-unit cardioid central subwoofer system with system layout (a) and simulated coverage patterns at (b) 40 Hz and (c) 90 Hz

The equal spacing configuration evokes higher SPL within the front rows of the audience (which could be a safety issue), while the left/right system does not produce this effect for the audience center. Also, the equally spaced system causes a power alley to arise due to the constructive interference from all units coinciding at the center axis of the system. Often, this power alley issue is ignored since the front-of-house (FOH) engineer is located at the venue center, which coincides with the optimal location for the best stereo effect from the main PA. Moving off center will gradually result in a diminished stereo effect and a reduction in low-frequency SPL. This is undesirable since the goal is to deliver equal low-frequency energy to a large audience area. It is also important that subwoofers are not positioned directly below the stage. This sort of placement has been demonstrated to result in the loss of subwoofer directionality[1] and is apparent in Figure 2.2 with the higher SPL on the stage due to reflections off the stage decking.

2.2 Practical issues

Subwoofer spacing and stage proximity often become moot points due to practical constraints. To begin with, the system must be transported to the venue. This requires a significant amount of truck space leading to greater fuel, driver and transportation permit costs. Due to a restricted production budget, the sound system is often reduced in size to fit the allocated truck space, resulting in a less than desirable system before it even reaches the venue.

Once at the venue, subwoofer placement usually is compromised to meet the sightline, set piece, lighting, video and venue requirements. These factors will cause the system configuration to be altered from venue to venue, requiring manual system tuning which there is not always an abundance of time to carry out. Larger venues can often provide the necessary roof support for flown subwoofer arrays which can help avoid many of the above mentioned issues with the cost of additional time to rig the system. An additional factor largely overlooked pertaining to ground stacked systems is the low-frequency absorptive properties of a large audience, which can potentially cause conflict between theoretical predictions and practical measurements in terms of front to back audience coverage[4].

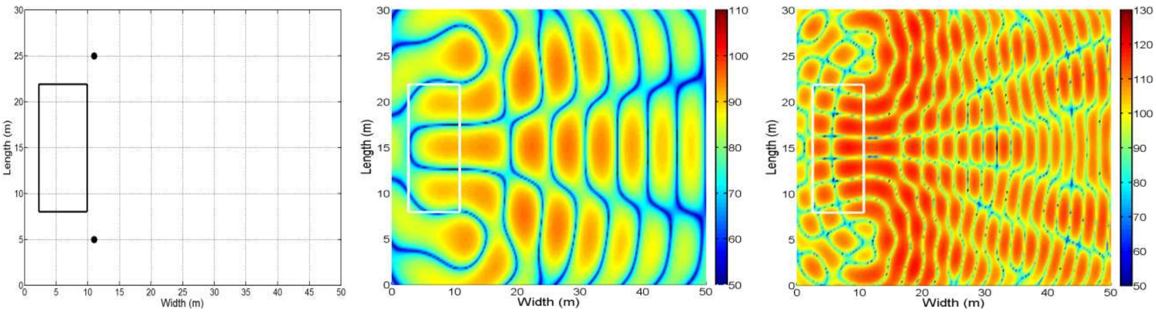
3 COMMON CONTROL TECHNIQUES

The practical issues that impact the design of a subwoofer system have led to the development of a number of alternatives to the standard ground-based in-line subwoofer systems. The majority of these solutions involve spatially-compact configurations, clear of sightlines. These systems benefit from using fewer well-configured subwoofers as opposed to many arbitrarily placed units, saving truck space, fuel and money.

3.1 Flown subwoofer arrays

Many larger venues are capable of supporting flown arrays, both for the main PA and subwoofer system. These systems benefit from being out of the way of audience sightlines as well as sufficiently far from the staging to avoid unwanted resonances. In addition to this, flown subwoofer arrays (and the main PA) benefit from less difference in propagation length between the closest and farthest listener. For ground-based systems the closest listeners are within a few meters of at least one of the system units while flown arrays are generally suspended many meters above the stage resulting in a more uniform front to back sound field where the audience in the first few rows receives approximately equal sound energy as those in the back rows. One disadvantage of flown subwoofer arrays is the loss of the Waterhouse effect[5], which gives ground-based systems 6 dB of added sound pressure output due to close proximity to the ground plane.

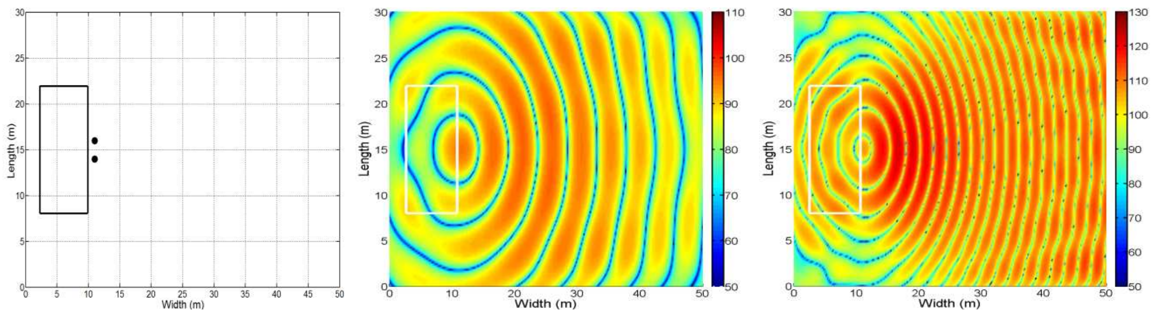
Most common configurations of flown arrays utilize left/right subwoofer vertical arrays flown directly beside the main PA hangs. These configurations suffer from pressure nulls similar to ground based clusters due to the spacing of the arrays. This problem is demonstrated in Figure 3.1 where 8-box left/right vertical flown arrays were simulated using the previously utilized virtual venue with the lowest box in the array at a height of 6 m.



(a) (b) (c)

Figure 3.1 8-unit left/right flown subwoofer arrays with system layout (a) and simulated coverage patterns at (b) 40 Hz and (c) 90 Hz

The flown left/right arrays do not provide adequate stage rejection due to their height above the stage. Following a similar line of reasoning to the ground based systems, a central flown subwoofer cluster can be simulated to demonstrate more even left to right coverage due to the decreased average horizontal spacing of the units (Figure 3.2).



(a) (b) (c)

Figure 3.2 8-unit centrally flown subwoofer arrays with system layout in (a) and simulated coverage patterns at (b) 40 Hz and (c) 90 Hz

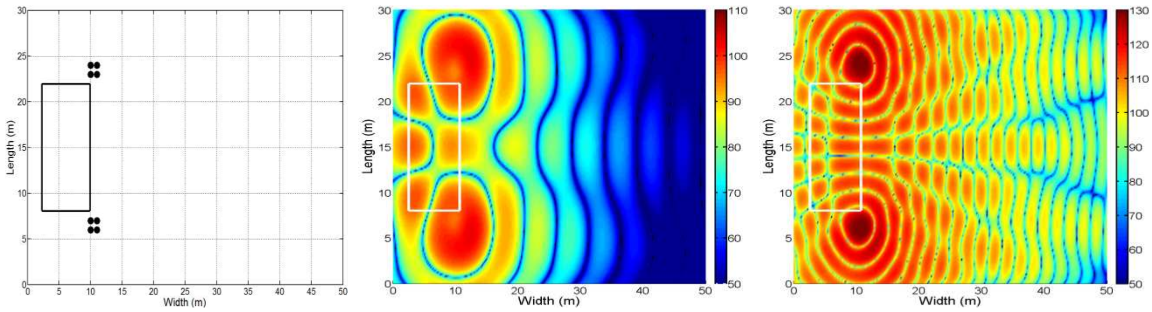
While this central cluster technique can provide more uniform low-frequency coverage it also restricts placement of video screens, limits any low-frequency stereo effects and often requires large trim heights to be sufficiently clear of the performance area. Stage rejection is superior to the left/right system and the spatial nulls have largely disappeared, giving relatively even left to right and front to back coverage at both 40 and 90 Hz.

3.2 Steerable clusters

A technique gaining popularity involves compact clusters of omnidirectional or cardioid subwoofers capable of applying individual electronic delay to create the desired cluster directivity. This technique has largely been developed and explored by Rat Sound[6] and Meyer Sound[7].

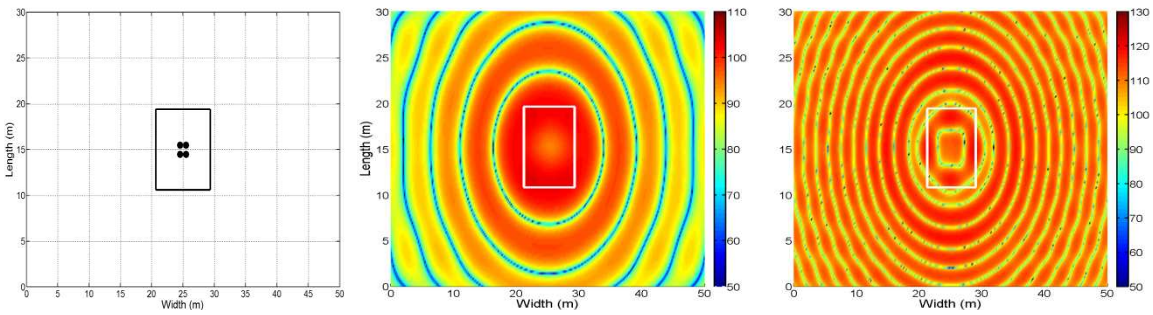
The most common occurrence of this technology is with ground-based left/right clusters. These clusters can achieve acceptable stage rejection while also covering over 270° of audience area; a common requirement for events in large sports arenas (Figure 3.3).

The disadvantage to the left/right cluster configuration is that the two clusters still operate independently of one another and result in the familiar pressure nulls. While spatial limitations prevent these clusters being placed in front of the stage, some touring systems have employed a central flown cluster for applications with the audience in the round (360°). This sort of configuration benefits from the close spacing of all subwoofers, giving a very even coverage pattern over the audience area (Figure 3.4).



(a) (b) (c)

Figure 3.3 Left/right steerable clusters for 270° audience coverage with system layout (a) and simulated coverage patterns at (b) 40 Hz and (c) 90 Hz



(a) (b) (c)

Figure 3.4 Central flown steerable cluster for 360° audience coverage with system layout (a) and simulated coverage patterns at (b) 40 Hz and (c) 90 Hz

Subwoofer clusters, both ground-based and flown, offer system engineers many more degrees of freedom towards directivity control. This added control, though, requires pre-planning and also fine-tuning from venue to venue; time that is either not always available or often allocated to other tasks. Also, as seen in Figures 3.3 and 3.4, clusters can provide the desired audience coverage but are not guaranteed to result in adequate stage rejection. Steerable clusters are an interesting technique for low-frequency control, but don't provide of a robust solution for coverage control.

4 CHAMELEON SUBWOOFER ARRAYS

An emerging technology aimed at small-room wide-area low-frequency correction utilizes chameleon subwoofer arrays[2] (CSA). The chameleon descriptor is used due to the system's use of individual subwoofer units with multiple degrees of freedom which can blend into an acoustical environment by matching the natural room response over a listening area.

The foundation of CSA technology departs from conventional single drive unit, single degree of freedom omnidirectional subwoofers by incorporating four source components within each unit: one omnidirectional and three dipolar (one in each primary rectangular dimension). While a conventional small-room subwoofer system of four units gives only four degrees of freedom, a similar system employing a CSA gives sixteen degrees of freedom, allowing for detailed correction procedures.

A CSA requires calibration measurements to generate the correction filters for each source component within the system. This setup operates using a single source component at a time while measuring the resulting impulse response at multiple target points within a listening area. The number of target points is governed by the system degrees of freedom. With the measurements complete, a user defines the target response at each target location, which can be the same or different for all points. The data is fed through a matrix equation to calculate the required filter coefficients to achieve the desired responses at each target point (Equation 4.1).

$$H = X^{-1}Y \tag{4.1}$$

where, *H* is an *n x 1* matrix of the complex correction coefficients, *X* is an *m x n* matrix of the measured frequency responses and *Y* is an *m x n* matrix with the desired frequency response for each target point. The system contains *m* target points and *n* source components. If *m* does not equal *n*, the larger of the two will be reduced to match the other, discarding the extraneous data. This calculation is performed over all frequency bins in the specified correction range.

To ensure system stability, a number of checks have been built into the CSA system. To avoid filter ringing due to correction attempts above the Schroeder frequency[8] (in the diffuse sound field range), an upper correction limit is imposed regulated by the room's volume and absorptive properties. Below the lowest room mode the system is only pressurizing the room, with little spatial variance across the area, so a lower correction limit is set just out of range of the lowest room mode. Lastly, dipolar sources are inefficient at very low frequencies[9], therefore the CSA is limited to omnidirectional operation for the lower correction range, as defined by the target point spacing[10]. Above this range all system source components will be active in the correction procedure.

To illustrate the potential room correction benefits with a CSA, a virtual room of dimensions 8 m x 6 m x 2.6 m was created with a four-unit CSA at room corner locations. A large listening area covers the central area of the space at a height of 1.6 m. Correction calibration was performed using the layout in Figure 4.1a, where points marked with an *A* represent target points in the omnidirectional-only band while points with a *B* are the target points for the remaining correction range. A virtual walking path was designed (Figure 4.1b) and tested with an MLS signal to determine the frequency responses at both target and non-target points within the path (Figure 4.1c).

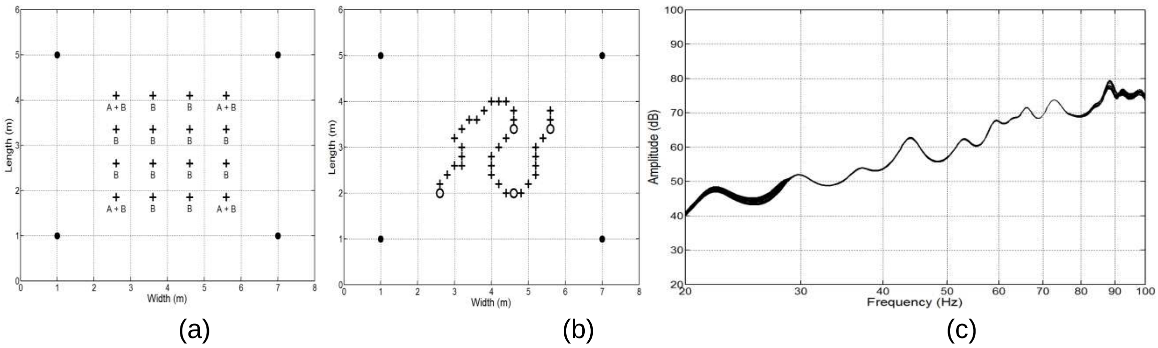


Figure 4.1 Small-room CSA implementation with (a) correction setup, (b) 36-point virtual walking test layout and (c) corrected frequency responses over the walking path

The uncorrected system results in 3.92 dB spatial variance across the walking path while the CSA-corrected system only exhibits 0.25 dB in spatial variance, a reduction of 93.8%. This highlights the power of a CSA for small room correction in terms of spatial variance reduction and/or real-time adjustment of specific target point frequency responses, due to the direct calculation approach.

5 LIVE SOUND APPLICATIONS

As alluded to in Section 3, a system that intelligently utilizes all subwoofers to create an overall coverage pattern would provide a much more robust solution to the low-frequency coverage problems faced in live sound. A CSA can easily be adapted to serve this purpose while fitting within current industry-standard hardware.

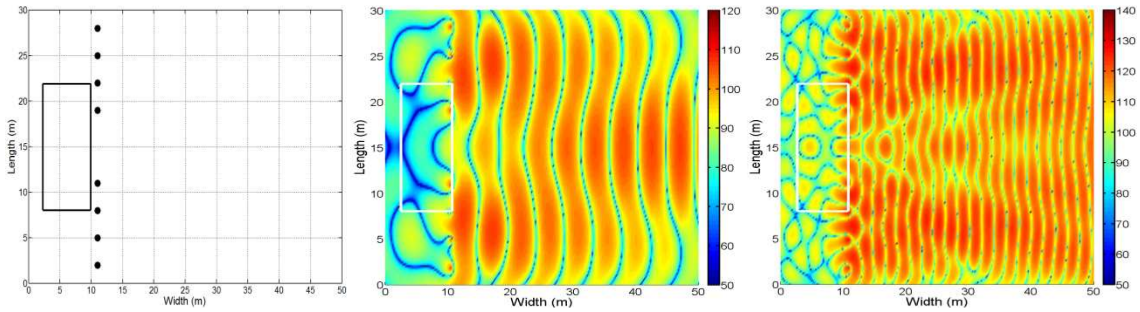
The CSA correction procedure is ideally suited for use with multi-component subwoofers, as described in the previous section; however, CSA correction can also operate on any subwoofer system given that each degree of freedom can be independently controlled. Cardioid subwoofers are becoming increasingly common in the industry, usually containing two independently controlled

18-inch drive units. The two distinct drive signals are principally generated within the system's control unit(s) which take the full-range input from the mixing desk and split the signal into relevant operating bands for each system component. CSA control can be applied by inserting an extra DSP unit in between the system processor and the power amplifiers. This supplementary unit will apply the control filters to the drive signals to create the target coverage pattern. Since the setup measurements are taken in line with the system processing, this procedure will not be adversely affected by any processing unit manipulations between the two unit drivers.

As with small-room CSA applications, the live sound CSA control procedure is limited by the number of degrees of freedom within the system and also the spacing of the target points. A subwoofer system driven by a four-mix amplifier rack on both the left and right sides of the stage will give a total of sixteen available degrees of freedom due to independent processing/amplification for front and rear drive signals (two degrees of freedom per subwoofer). Frequencies with half-wavelengths shorter than the mean spacing between target points will not result in a uniform coverage pattern across the audience/stage area; rather pockets of control will exist caused by the wide spacing of target points. Small room CSA correction procedures generally recommend a more conservative one-quarter wavelength maximum spacing, but half-wavelength spacing is sufficient for the less detailed live sound CSA control procedure.

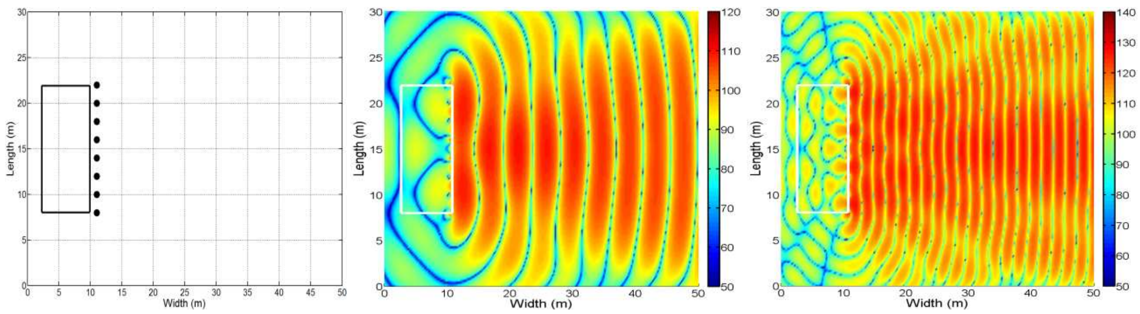
5.1 Unprocessed system results

A 50 m x 30 m outdoor virtual venue was set up containing an eight-unit cardioid subwoofer system with left/right placement. Simulations were conducted in two-dimensions to provide simulation time efficiency. As with previous test, the system coverage pattern was simulated at 40 and 90 Hz for the unprocessed system (Figure 5.1). Following the convention of passive unit placement, an equally-spaced unprocessed central system was also simulated (Figure 5.2).



(a) (b) (c)

Figure 5.1 Unprocessed left/right eight-unit cardioid subwoofer system with system layout (a) and simulated coverage patterns at (b) 40 Hz and (c) 90 Hz



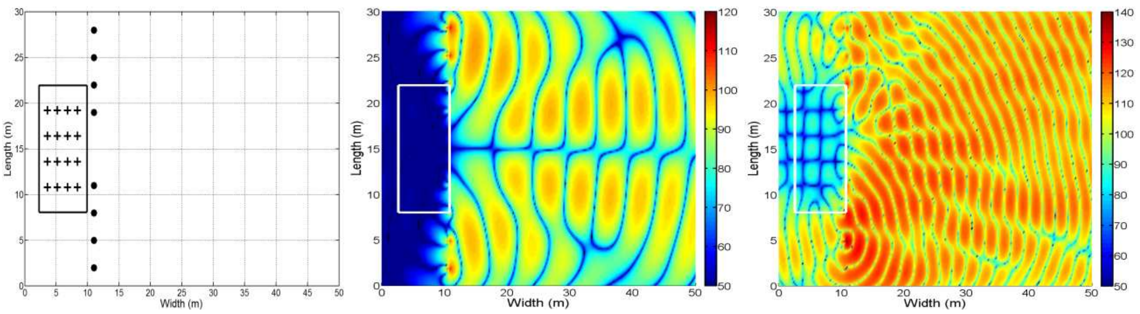
(a) (b) (c)

Figure 5.2 Unprocessed central eight-unit cardioid subwoofer system with system layout (a) and simulated coverage patterns at (b) 40 Hz and (c) 90 Hz

The unprocessed systems give reasonable audience coverage patterns, although the left/right configuration does result in the expected spatial nulls at certain points within the audience. Both systems deliver approximately 10 – 15 dB stage rejection, as compared to SPL in the audience. At loud rock concerts this could amount to an SPL of over 110 dB in some areas of the stage, which can be unsafe for musicians and other production staff to be working in on a daily basis.

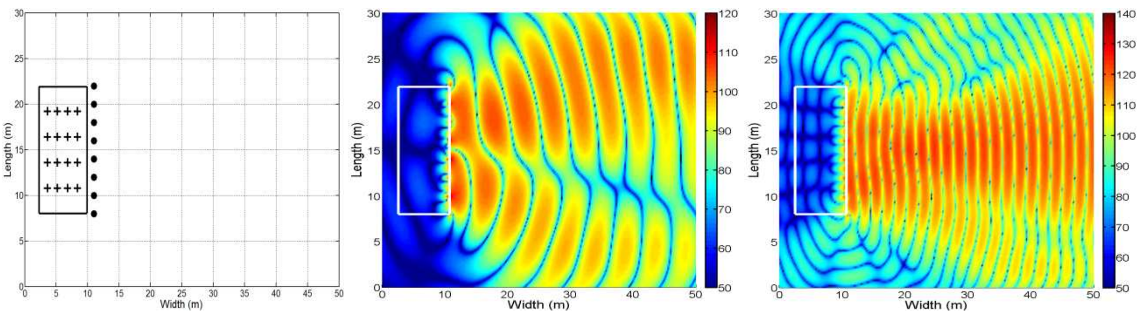
5.2 Chameleon subwoofer array results – stage control

A CSA can be utilized in an attempt to minimize SPL on stage to ensure a safe working environment. Identical systems as in Figures 5.1 and 5.2 were utilized for the CSA methodologies with target points arranged in a grid pattern on the stage. All target responses were set to the measured average response, but with approximately 40 dB attenuation. In addition, individual propagation delay was factored into each target response, based on measured delay time to each target point. Audience coverage is not considered in this approach, although overall system output is set to match the uncorrected system, so similar audience coverage patterns should endure. The eight-cardioid unit systems allow for sixteen degrees for freedom. As before, both configurations were tested at 40 and 90 Hz (Figures 5.3 & 5.4).



(a) (b) (c)

Figure 5.3 CSA stage controlled left/right eight-unit cardioid subwoofer system with system layout (a) and simulated coverage patterns at (b) 40 Hz and (c) 90 Hz (**+** = target point)



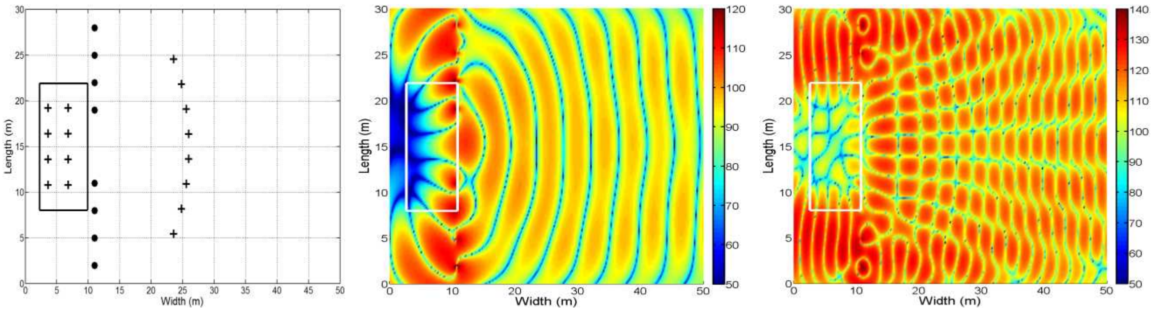
(a) (b) (c)

Figure 5.4 CSA stage controlled central eight-unit cardioid subwoofer system with system layout (a) and simulated coverage patterns at (b) 40 Hz and (c) 90 Hz (**+** = target point)

The stage-only CSA control results in significantly greater stage rejection (up to 50 dB in some cases), but also highlights certain problems. First, since the audience area is not considered in the control procedure, there are clear deviations from the unprocessed coverage patterns, most noticeably with large central nulls for the 40 Hz trials. Second, the 90 Hz trials show less stage rejection than at 40 Hz. This is due to the target point spacing issue. The mean spacing is 3 m which dictates that accurate, uniform control over the entire target area will only exist below approximately 60 Hz. At 90 Hz, therefore, there are pockets of control with the outlying areas not receiving clear benefit from the CSA procedure.

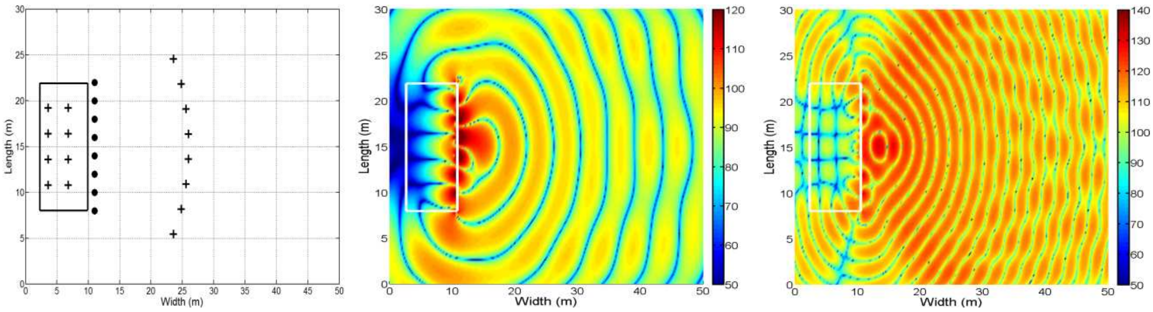
5.3 Chameleon subwoofer array results – stage + audience control

To evade the problems present with stage-only CSA control, the sixteen target points can be divided between the stage and audience area. The stage target responses will remain unchanged from the previous examples, while the audience points will target the measured average response across all points. This technique should provide more even audience coverage while maintaining the stage rejection (although to a lesser extent due to the reduction in stage target points). Again, control is limited to the target spacing, both in the audience and on stage, to around 60 Hz. Identical system configurations to those in the previous examples were utilized, tested at 40 Hz and 90 Hz (Figures 5.5 & 5.6).



(a) (b) (c)

Figure 5.5 CSA stage + audience controlled left/right eight-unit cardioid subwoofer system with system layout (a) and simulated coverage patterns at (b) 40 Hz and (c) 90 Hz (**+** = target point)



(a) (b) (c)

Figure 5.6 CSA stage + audience controlled central eight-unit cardioid subwoofer system with system layout (a) and simulated coverage patterns at (b) 40 Hz and (c) 90 Hz (**+** = target point)

The stage + audience controlled CSA results show notable improvement over the stage-only control. The audience target points ensure that the coverage pattern is evenly distributed throughout the audience area while still minimizing pressure on stage. The downstage edge of the stage experiences relatively high SPL due to the target points' upstage placement. Again, the 90 Hz results show pockets of control as opposed to uniform control which is due to the wide target spacing, limiting uniform control to below 60 Hz. The central configuration, however, does result in even wide-audience coverage at 90 Hz, largely due to the naturally even coverage of the configuration.

6 CONCLUSIONS & FUTURE WORK

A live sound application of chameleon subwoofer array (CSA) low-frequency control has been presented as a new technique to limit the amount of low-frequency energy on stage while creating a uniform pressure distribution over a large audience area. While conventional control systems can provide up to around 20 dB attenuation on stage, largely due to the cardioid radiation pattern of the subwoofer units, CSA-controlled subwoofer systems have been shown in simulations to be capable of up to 50 dB of rejection while maintaining uniform audience coverage.

The live sound CSA control technique operates within the existing framework of industry-standard systems, utilizing the independent front and rear drive-unit processing/amplification capabilities to allow for two degrees of freedom for each cardioid subwoofer. This method can be inserted into a conventional system in between the system processor and the power amplifiers, minimizing the need for expensive new hardware.

A drawback to the CSA system is the target point spacing restrictions. Wider spacing corresponds to a lower control frequency limit. Above this limit control will exist in pockets, but will not be uniform. Tighter target point spacing can raise the frequency limit, but will result in a narrower control area unless additional target points are added, which would require additional degrees of freedom within the subwoofer system.

Future work required in this area includes running simulations in closed environments to judge the effectiveness in smaller concert halls and other venues. As the system can easily fit into existing sound systems, real-world testing can theoretically be performed to confirm the effectiveness of the CSA live sound control procedure.

Overall, CSA control can potentially bestow a robust solution to the difficult problem of providing equal low-frequency audience coverage while keeping SPL to a minimum onstage. It differs from existing methodologies in the fact that all units within the CSA operate synchronously to give the desired coverage pattern while other systems use independently operating subwoofers which require time-consuming manual fine tuning from venue to venue.

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