PRACTICAL BENEFITS & LIMITATIONS OF DIGITALLY STEERED LOUDSPEAKER ARRAYS

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Abstract

The capability of digitally steered line array loudspeakers to create directional patterns of varying beamwidth, and to steer those patterns off the primary axis of the device is well known. However, significant additional benefits may be realized with non-traditional coverage patterns, and by exploiting the horizontal invariance of the vertical pattern to more precisely cover typical audience areas. The practical limits of off-axis steering and beam forming will also be characterized, so that practitioners may assess the potential impact of any unintended directional artifacts.

0 INTRODUCTION

Digitally steered arrays are capable of creating directional patterns of varying beamwidth that can be steered off the primary axis of the device. The ability to cover an audience from an elevated position without physically tilting the loudspeaker is a significant benefit in itself. Additional acoustical benefits may be realized by employing non-traditional coverage patterns. The horizontal invariance of the vertical patterns results in more precisely covered typical audience areas. In this paper, we will first discuss a new method of specifying the desired coverage. Second, we will discuss some non-obvious benefits offered by digitally steered arrays. Third, we will characterize and discuss the limitations of off-axis steering and beam forming. Through these explorations, we hope to make sound system design practitioners familiar with both the benefits and the limitations of digitally steered arrays, thereby determining their suitability to a given acoustical environment.

Throughout the paper, we will provide relevant examples from the program, FChart (a proprietary measurement and modeling tool), and from the program, EASE, which is a product of ADA Acoustic Design Ahnert. The authors' work in digital steering began in the context of a large-scale sound reinforcement system, which was described in a prior AES paper in 1997.² This work also led to improvements in precision loudspeaker measurements, which were described in an AES paper entitled, "Loudspeaker Complex Directional Response Characterization" by William R. Hoy and Charles McGregor, presented in 2001.³ The current implementations of digitally steered arrays are compact, simple to operate, and are intended for smaller scale applications.

0.1 Digitally Steered Array Loudspeaker Modules

The loudspeaker systems in question consist of the two models discussed in the paper, "Implementation of a Wide-Bandwidth, Digitally Steered Array" by David W. Gunness and Nathan D. Butler. For clarification, the first loudspeaker system is a 16-driver, 2-way full-range system with separate arrays of low frequency and high frequency transducers. This loudspeaker system consists of eight horn-loaded 1-inch-dome high frequency transducers and eight, 4-inch, low/mid frequency transducers. The high frequency horns are stacked in a vertically adjacent line, while the low frequency transducers are staggered so that they approach being overlapped. Both conditions provide the spacing density required for optimum directional control. High transducer density is needed to achieve the required close coupling of the individual transducer outputs.

The second model is a one-way low/mid frequency loudspeaker consisting of the 8-transducer low/mid frequency section of the two-way loudspeaker described above. Because of the lack of high frequency drivers, this loudspeaker is physically shorter. The length of a low frequency array determines the extent of its control at low frequencies. For applications where beamwidth control to lower frequencies is desired, this loudspeaker can be combined with like loudspeakers or the full-range loudspeakers to construct arrays of any length. In addition, the one-way model can be used for voice-only and background music applications

In addition to the transducers, each loudspeaker contains a DSP subsystem which implements steering filters for each transducer, cross-over filters, and an input section including equalization, high-pass and low-pass filtering, limiting and priority override. The loudspeakers also contain the necessary amplification for each transducer. A specialized software application is used to adjust the directional pattern and front end settings. To build arrays, modules can be linked together via an RS-485 cable for control, or link cable for combined control and audio signal.

The loudspeakers are tall and narrow, and are intended to be positioned in a vertical orientation. This makes them particularly well-suited to applications where they must unobtrusively blend in with the environment. Figure 1 shows both of the loudspeakers described. The loudspeakers can be used individually or in larger arrays by placing multiple loudspeakers in end-to-end configurations. Figure 2 shows a few examples of multiple-loudspeaker arrays. When the listening area is below the array, the orientation with the high frequency section on the bottom is preferable because this effectively reduces the steering angle required of the high frequency section relative to the low frequency section.



Full Range Loudspeaker LF/MF Loudspeaker

Fig. 1. Digitally Steerable Loudspeaker Modules



Fig. 2. Examples of Multi-Enclosure Clusters

0.2 Digital Steering

Digital steering is accomplished by providing a unique block of signal processing for each transducer in the array. In the current implementation, this processing

consists of a combination of conventional and proprietary digital filters. For the 2way loudspeaker, crossover filters and equalization are also included. The amplitude and phase response is manipulated in such a way that the sound waves largely cancel outside the intended coverage area, but interfere more constructively within the intended coverage area. A combination of direct calculation and iterative optimization determines the settings for each channel.

In addition to the processing block for each transducer, user-accessible input signal processing blocks are employed (Audio A and Audio B in Figure 3). This includes parametric equalization, compression/limiting, and signal delay. Figure 3 shows the complete block diagram of the first loudspeaker discussed with its digital signal processing (DSP) blocks.



Fig. 3. Block Diagram of DSP Subsystem

1 SOFTWARE INTERFACE

1.1 Software Introduction

Digitally steered arrays must be accompanied by software that allows the users to "program" their settings. For a particular array, the position and orientation of each individual enclosure must be communicated to the software, as well as the desired coverage area. After the optimum signal processing settings are calculated, they are uploaded from the computer to the signal processors in the array so that the intended design may be realized. Traditionally, sound system designers have specified loudspeaker coverage in terms of aiming angles and direction. While the traditional specification is effective in some situations, it is unnecessarily limiting. To realize the full potential of digitally steered arrays, we introduce a new method of specifying the desired coverage.

1.2 Traditional Directionality Specification

Several common terms have been used to characterize loudspeaker directionality over the years. "Directivity index," while a useful measure, was not sufficiently precise for detailed system layout work because it ignored the differences between the horizontal and vertical behavior. The horizontal and vertical beamwidth was more descriptive, and served both as an intuitively useful specification and as a figure of merit, when plotted against frequency. Because many practitioners are comfortable and familiar with beamwidth specifications, the software supports a simple, traditional, method for specifying the vertical coverage pattern. The beamwidth is specified, along with an off axis steering angle labeled, "steering" – to substitute for the physical aiming of the loudspeaker. Figure 4 defines the terms.

The third parameter in the traditional method is "focal distance," which has two effects on the end result. It creates a beam whose edges correspond to the nominal beamwidth at the specified distance; and, it adjusts the steering angles so that the beams from the high frequency and low frequency sections converge at the focal distance, even though they are located in slightly different places. Figures 6 illustrates these two effects. In normal use, the primary effect of this parameter will be on the pattern edge. If the entered focal distance is too long, the lower pattern edge might be a bit brighter than normal, because the low frequency array would not be steered down enough. If it is set too short, the lower pattern edge might lack brightness.

The focal distance parameter also allows the system to create a beam smaller than the array that produced it. In other words, a zero-degree entry for beamwidth will actually produce a converging beam which achieves maximum pressure at the focal distance.



Fig. 4: Traditional Coverage Specification Method Terminology



Fig. 5: Beam Convergence at the Focal Distance

1.3 Audience-Coverage Directionality Specification

While the traditional specification is effective in some situations, it is unnecessarily limiting. Digital steering is capable of producing a beam which varies in intensity within the angular constraints of the beam. All that is required is a definition of the desired coverage area, and the steering algorithms can attempt to fit the coverage in both direction and distance. For the vast majority of applications, a sufficient level of detail can be obtained with a simple, two-segment approximation of the cross-section. The two segments are defined by a start point, an inflection point, and an end point. Such a cross section is illustrated in figure 6.



Fig. 6. Two-Segment Definition of Listening Area

The software interface, illustrated in figure 7, implements both the traditional method and the listening area method of specifying coverage. In the upper left hand corner are the parameters that define the two-segment listening area. The three points defined by these parameters are represented graphically by the blue lines in the venue cross section. The last point might represent the end of a contiguous listening area, or it might represent the last seat in a balcony. In the case of a room with a balcony, the inflection point may be placed somewhat arbitrarily, to either encourage or discourage aggressive coverage of the back of the main floor, under the balcony.



Fig. 7. Sample software interface

The defined listening area is displayed even when the traditional beamwidth method of specifying coverage is active. This allows the traditionally defined beam and its off-axis steering to be matched to the profile of the room.

Having established the coverage goals for the loudspeaker cluster, the next task is to determine a set of digital signal processing parameters that achieve the desired results. While delay adjustments alone are capable of achieving significant beneficial steering and beam forming, one or more of a variety of secondary techniques can be used to improve the results over a simple delay scheme. These techniques affect the precision of the polar response, the relative smoothness and consistency of the frequency response in various directions, and can alternately enhance either intelligibility or musicality. By varying the degree to which each technique is employed, the software allows the steering parameters to be optimized according to the specific needs and objectives of a particular installation.

The user communicates those objectives by way of a slider control which allows the objective of the steering algorithm to be varied from "Spectral Consistency" to "Maximum Projection," with several intermediate settings in between. The affect of this setting will be explored in Section 2.4, below.

2 CHARACTERISITCS OF DIGITAL STEERING

2.1 Conventional Line Array Tilted Down vs. Digitally Steered Beam

Digitally steered arrays are capable of creating directional patterns of varying beamwidth and steering those patterns off the primary physical axis of the device. A major advantage of such an array is the character of the radiation pattern. The pattern produced by a digitally steered array is not the same as that produced by tilting a conventional loudspeaker with the same horizontal and vertical beamwidths.

A typical loudspeaker that is tilted down to cover a listening area creates several problems. First, the geometry of the down-tilted loudspeaker's pattern is arc-shaped with a main lobe emanating from its primary physical axis. The width and directionality of the beam results in inadequate coverage across the front area of the intended listening area. In addition to this, the pattern produced by a down-tilted loudspeaker projects a distinct band of energy onto the side walls of the venue, which of course arrives at the listener as a late reflection. This reflection can be nearly as strong as the primary arrival which reaches the listeners directly. An example of this behavior is shown in Figure 8a.

2.2 Suppressing Lateral Reflection

On the other hand, digitally steering an array produces a far more consistent SPL across the intended coverage area. With the long dimension of the array vertical and signal processing used to direct the energy downward, the side radiation projects downward at the same angle as the front radiation. This provides far more uniform sound levels in the listening area. In addition to this, the energy that is directed to the side walls is much lower in level and creates a very different reflection pattern off of those walls. The reflected sound is directed into the floor or the nearby seats along the wall early enough in relation to the direct sound that it can actually enhance intelligibility. See Figure 8b.



Fig. 8A. Conventional Line Array Coverage, Tilted Down



Fig. 8B. Digitally Steered Coverage

2.3 Back Radiation

It is important to be aware of the back radiating characteristic of a steered array. Because the enclosures are less than 25 cm wide, the horizontal beamwidth does not narrow to 180 degrees until 800 Hz. At frequencies lower than 800 Hz, the back radiation will be increasingly strong. Furthermore, the backward radiating beam will be steered down at the same angle as the front radiation. This can be an important consideration if these arrays are suspended in mid-air, rather than mounted to a wall. When mounted to a wall, the back radiation reflects back into the front hemisphere with the same downward angle as the front radiation. Consequently, its effect is relatively benign.



Fig. 9: 15 degree beam steered -10 degrees, showing back radiation

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Figure 9 displays the back radiation for a 15 degree beam steered down 10 degrees. Note that the level of the back lobe at 316 Hz is within about 5 dB of the level of the front lobe. At 800 Hz, there is about a 12 dB differential. Figure 10 shows the same array mounted to a wall. Note that the polar response above 300 Hz is not appreciatively affected by the presence of the wall, even though there is a significant contribution from the back radiation from 300 Hz to 800 Hz. The apparent widening of the 200 Hz beam is actually an indication of destructive on-axis interference between the front lobe and the reflected back lobe.



Fig. 10: Steered array mounted on a wall, same settings as figure 10

2.4 Spectral Consistency vs. Projection

In a well damped room with naturally high intelligibility, considerable flexibility exists as to how a sound system may be tuned. One might accept a significant degree of variability in the SPL produced in different parts of the room, in order to obtain a consistent spectral balance throughout. In a hard, reverberant, challenging room, on the other hand, one might accept a significant degree of spectral variation, in order to obtain the maximum possible direct-to-reverberant ratio. This is the trade-off offered by the spectral consistency vs. projection slider. As illustrated in the uppermost chart in figure 12, the high frequency coverage can be matched very precisely to the requirements of the room, in order to obtain nearly equal SPL throughout. However, the same degree of control is not possible at low frequencies. As a result, the direct sound delivered to the farthest listener will be considerably brighter than that delivered to the closest listener.



Fig. 11: Varying The Objective from Maximum Projection to Maximum Spectral Consistency, response calculated at 5 m, 15 m, & 25 m

With maximum spectral consistency selected (the lowest chart in figure 12), the spectrum of the direct sound is quite consistent up to about 7 kHz, and the response at the nearest microphone (shown in red) is somewhat smoother.

This consistency and response smoothness, however, comes at the expense of maximum output. All of the charts are normalized to represent equal drive level to the hardest-working transducer. So, the approximate 7 dB reduction in the long-throw response (shown in green) is representative of the maximum level achievable at the back of the room. The reason for this is that the spectral consistency setting allows the use of steering filters which affect the overall drive level to the various transducers. Consequently, some of them will be running at less than maximum level when the hardest working one reaches its maximum. With the slider in the maximum projection position, the transducers are all driven equally hard. Driving all the transducers equally has been found to produce the most clearly defined focus at the farthest listener, which results in maximum intelligibility. It also has the side effect of maximizing the total sound power output capability.

3 PERFORMANCE LIMITS

Regarding the performance of digitally steered systems, two of the most frequently asked questions are, "How far off axis can the system be steered?" and "What range of beamwidths can it achieve?" Unfortunately, these are very difficult questions for which to provide simple answers. In order to provide a performance limit, one must define what constitutes a failed setting. This definition is not always obvious.

3.1 Off Axis Steering Limits

It is possible to create a focal point as much as 90 degrees off axis. However, the primary limitation for off-axis steering is out-of-beam leakage. To define a limit for off-axis steering capability, then, one must define the limit of acceptable out-of-pattern response. In particular, narrow beams steered radically off axis produce severe out-of-beam leakage. The acceptability of such leakage may depend on the the acoustical properties present in a prospective application.

As a starting point, let's look at a relatively narrow beam, steered at various angles off axis. Figure 12 shows the polar response of a small array (one of the two-way enclosures) projecting a 30 degree beam, and steered 10 degrees off axis.



Fig. 12: Small Array, 30-degree beam steered – 10 degrees

There is little to criticize in this set of polars, though there is a hint of grating lobes beginning to form between +60 and +90 degrees at 1250 Hz to 1600 Hz.

Figure 13 displays the polars for a 30 degree beam steered down 30 degrees. In this example, the grating lobes have become more obvious, particularly at 8 kHz, at which frequency the out-of-pattern lobe nears -6 dB from the main beam.

Figure 14 displays the polars for a 30 degree beam steered down 50 degrees. With the grating lobe at 8 kHz reaching the same level as the main lobe, this setting is clearly "beyond the steering limit". However, this could still be a useful configuration in an application in which the upward-directed high frequency energy was deemed not to be a problem, or in which the system could be low-passed at 5 kHz (i.e., speech only).

Based on this series of data, one might state the limit of steering as -30 degrees; with the criteria being that the largest grating lobe is more than 6 dB lower in level than the main beam.



Fig. 13: 30-degree beam, steered – 30 degrees



Fig. 14: 30-degree beam, steered –50 degrees

Having established that the limit of off-axis steering is 30 degrees for a relatively narrow beam, let's look at an example of an audience-coverage steering setting. In the example presented in Figure 15, the coverage extends to below –60 degrees; yet, there is barely a hint of a grating lobe at 1250 Hz. Clearly, the previous analysis does not hold for a complex audience-coverage beam. In this configuration, most of the energy is directed nearly axially, with only a small portion of the energy directed in the extreme off axis direction.

In fact, experience has shown that the system is useable down to -90 degrees when the audience-coverage steering algorithm is employed.



Fig. 15: Audience Coverage beam, (3.5 m, -6 m), (20 m, -5 m), (30 m, -2 m)

3.2 Beamwidth Limits

The beamwidth limits are much easier to quantify. The customary practice when specifying the effective frequency range of control for constant directivity horns is to specify the lower frequency at which the beamwidth is 1.5 times nominal, and the upper frequency at which the beamwidth collapses to 2/3 of nominal. If we model a 150 degree beam, and inspect the polars (Figure 16), we see that the beamwidth collapses to 100 degrees at about 5 kHz. If 5 kHz is sufficient bandwidth for a given application, then a 150-degree beam could reasonably be used.

If we model a 90 degree beam (Figure 17), we see that the beamwidth stays wider than 60 degrees beyond 10 kHz, which exceeds the limit of horizontal control. Consequently, it is reasonable to state the maximum beamwidth as 90 degrees, without stating a frequency limitation.



Fig. 16: Small array configured for 150 degree beam



Fig. 17: Small array configured for 90 degree beam

4 CONCLUSION

A modular, digitally steered loudspeaker array and its associated control interface was described. This interface implements a method of specifying coverage which incorporates the coordinates of the listening area, rather than limiting input to the traditional terms, "beamwidth", and "aiming angle".

Some of the unique characteristics of digitally steered arrays were explored. A valuable benefit is the inherent advantage of a pattern which is directed downward both on axis and off axis. This pattern tends to reduce lateral reflections in a room, and provide broader coverage in the nearfield. The unique nature of these arrays' back radiation was also noted.

Finally, the limits of acoustical performance were explored, and the limiting factors identified. The audience-coverage method of specifying the directionality target was determined to be especially immune from grating lobes.

5 REFERENCES

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