IMPLEMENTATION OF A WIDE-BANDWIDTH, DIGITALLY STEERED LOUDSPEAKER ARRAY

David W. Gunness & Nathan D. Butler

Eastern Acoustic Works, Inc.
1 Main St., Whitinsville, MA 01588
PH: 508-234-6158 FAX: 508-234-6479
e-mail: david.gunness@eaw.com
e-mail: nathan.butler@eaw.com

Abstract

Many potential applications of digital loudspeaker steering require a wide bandwidth implementation in order to benefit from the flexibility and control offered by this technique. The requirements for effective steering are explained with examples, and used to establish physical criteria for a useful system. An implementation is described which meets these criteria with a high-density, multi-way source array and integrated processing and amplification. The design parameters, the capabilities, and the practical limitations of this system will be explored and demonstrated.

0 INTRODUCTION

Digital signal processing, when applied to each element of a line source, can produce wide variations in directionality and propagation direction. Unfortunately, the effectiveness of the technique is limited to a finite frequency range determined by the source characteristics and their spacing. While a narrow-bandwidth (~4 octaves) implementation can be used effectively in some applications, a wide-bandwidth (~7 octaves) implementation is suitable to a much broader range of applications. To create a wide-bandwidth steered array, it is first necessary to establish the physical requirements for success.

To achieve a useful degree of steerability above 8 kHz, a source spacing of less than 50 mm is required. This can be accomplished by using very small sources. However, to achieve useful output levels and directional control as low as 100 Hz requires larger transducers and a relatively long array. The solution to these conflicting requirements is to create a two-way system with separate arrays of low frequency and high frequency transducers.

Modeled sources were evaluated at various spacings to determine the optimum arrangement for steerability. Effective steering is dependant upon source spacing that is proportional to the minimum wavelength reproduced. Should the source spacing exceed the minimum wavelength, off axis lobes can result that are equal in magnitude to the primary lobe. This is the result of differences in arrival times from said sources. In order to minimize arrival differences, source spacing must be kept at a minimum. To further prevent off axis lobes at high frequencies, an edge-to-edge linear array of horn mouths is much more effective than a linear array of direct radiators.

1 ACOUSTIC REQUIREMENTS

1.1 High Frequency Analysis

To determine the effect of source size and spacing on the directional behavior of a steered array, it is instructive to compare the performance of a single, ideal, continuous, line source with a linear array made up of multiple sources. Figure 1 illustrates an ideal, continuous, 30° arc source. The source has been filtered to reject frequencies below 1 kHz. Magnitude response of the source is shown at 0°, 10°, and 60° off axis. Polar response shows that the source exhibits an ideal 30° pattern above 2 kHz.
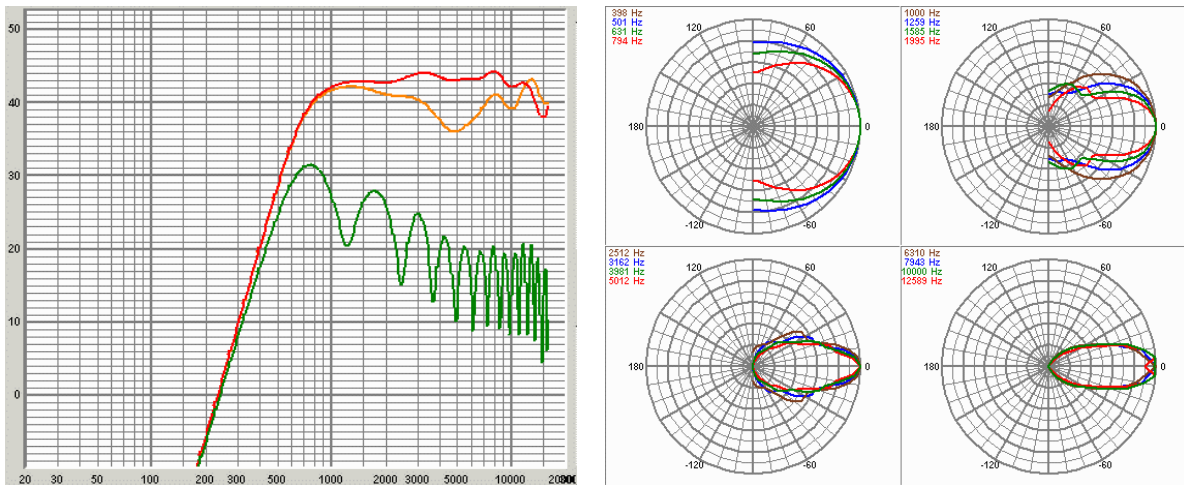

Fig. 1. Ideal, continuous, 30° arc source. Magnitude - Red: 0°, orange: 10°, green: 60°. Polar - 400 Hz to 12.5 kHz, 1/3 octave.

Figure 2 illustrates the response of this source at the 60° location. For clarity the magnitude response from figure 1 is displayed again. The impulse response exhibits a positive-going pulse corresponding to the nearest edge of the source and a negative-going pulse corresponding to the far edge of the source, spaced about 0.8 ms in time. The details of this topic are outlined in "Loudspeaker Acoustic Field Calculations with Application to Directional Response Measurement", presented at the 109th Convention of the Audio Engineering Society, 2000[1]. Note that "peaks" and "valleys" in the magnitude response occur approximately every 1.2 kHz, corresponding to a 0.8 ms period.
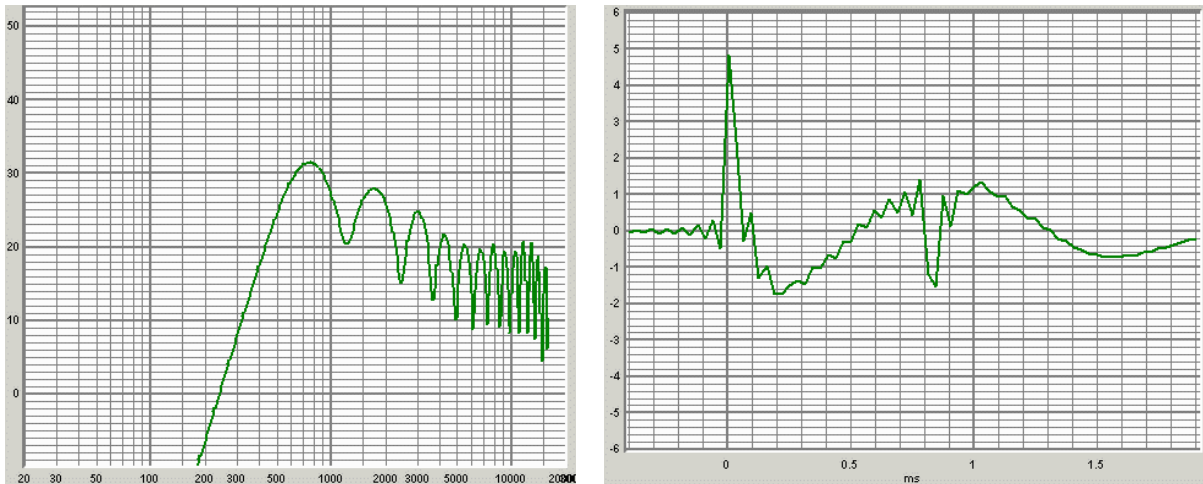
Fig. 2. Response at 60° off axis: ideal, continuous, 30° arc source.

Figure 3 illustrates an array of eight point sources spaced on 41 mm centers. Point sources are used in this example to emulate the characteristics of a very small transducer. The magnitude response of the array is shown at 0°, 10°, and 60°. Proper delay has been applied to individual sources to achieve a 30° pattern. The polar response shows that the array exhibits a nominal 30° pattern above 2 kHz. Note the similarities to the ideal source from figure 1 within the array's 30° pattern. However, outside this pattern, the array deviates significantly from the ideal source. Above 6.5 kHz, the array suffers from off axis lobes, a result of the source spacing exceeding the reproduced wavelength. Lobes are clearly seen in the polar response at 6.3 kHz, 8 kHz, 10 kHz, and 12.5 kHz.
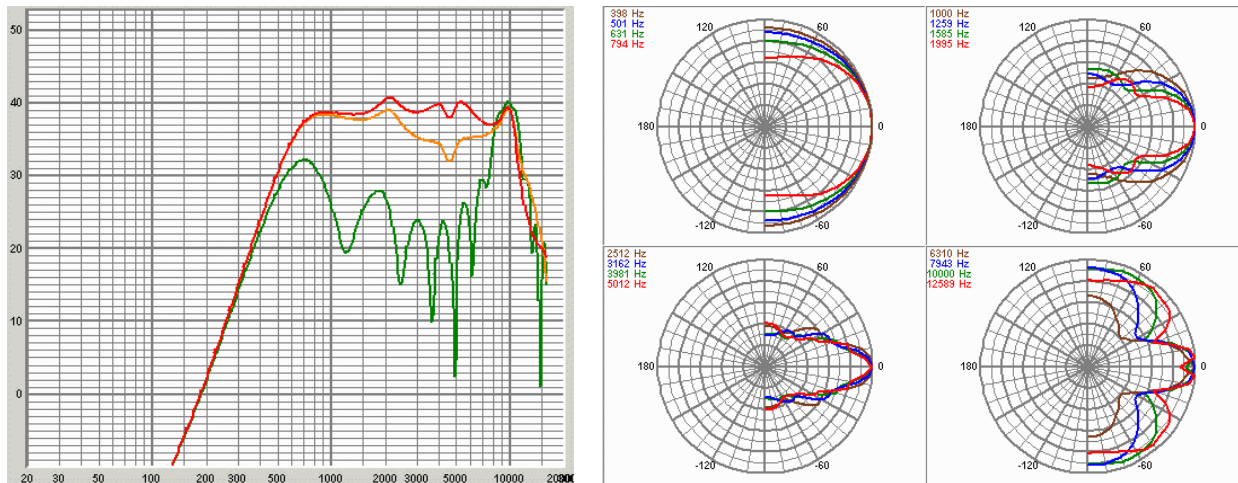

Fig. 3. Array of eight point sources on 41 mm centers, processed to 30° pattern. Magnitude - Red: 0°, orange: 10°, green: 60°. Polar - 400 Hz to 12.5 kHz, 1/3 octave.

Perhaps more interesting is the impulse response of the array at 60°, shown in figure 4. Here, rather than the two distinct positive and negative pulses shown in figure

2, a positive and negative pulse for each source is discernible. Each pulse's negative trailing edge lines up in time with the positive leading edge of the next pulse.
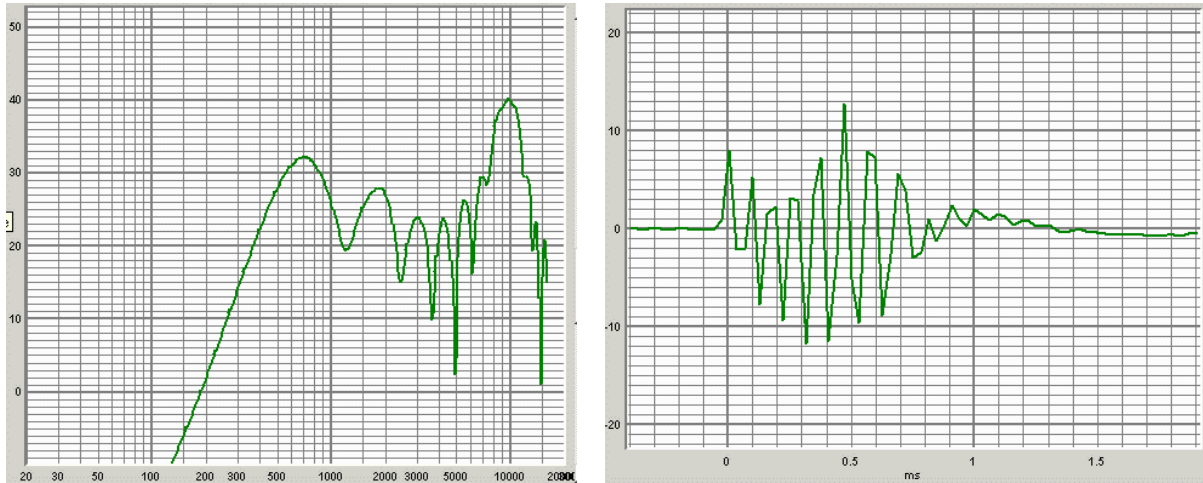

Fig. 4. Response at 60° off axis: array of eight point sources on 41 mm centers, processed to 30° pattern.

The directional characteristic of a line of directional sources is known to be the mathematical product of the directional characteristic of a single element of that line, and the directional characteristic of a line of point sources with the same arrangement. To achieve spacing as small as possible, very small sources are required. Since the directional characteristics of a small source mimics that of a point source within the audible frequency range, the only means of overcoming the limitations of the array of point sources shown in figures 3 and 4 above would be to decrease the source spacing beyond what is physically possible, or alter the pattern of the individual sources.

Figures 5 and 6 illustrate an edge-to-edge array of high frequency horns on 41 mm centers. Again, proper delay has been applied to individual sources to achieve a 30° pattern. The polar response shows that the array exhibits a nominal 30° pattern above 2 kHz. Unlike the array of point sources, the vertical pattern of each source in this array is controlled by its horn. The result is an overall polar response that more closely matches the behavior of the ideal continuous source outlined above.
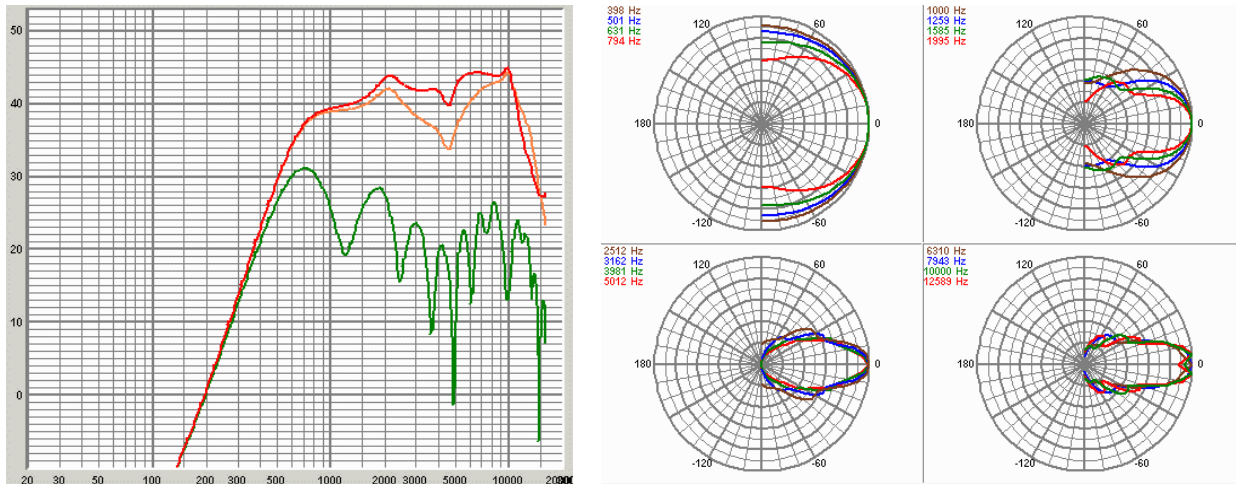
Fig. 5. Array of eight horns on 41 mm centers, processed to 30° pattern. Magnitude - Red: 0°, orange: 10°, green: 60°. Polar - 400 Hz to 12.5 kHz, 1/3 octave.
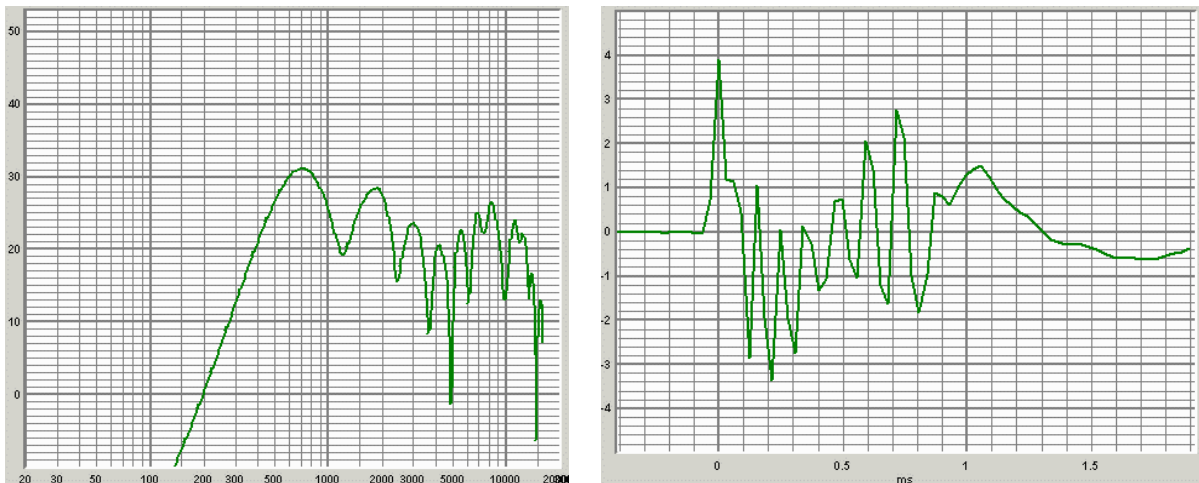

Fig. 6. Response at 60° off axis: array of eight horns on 41 mm centers, processed to 30° pattern.

1.2 Low Frequency Analysis

In order to successfully steer the upper frequency range of a linear array of low frequency devices, the optimum spacing calls for small cone transducers to be overlapped, a physical impossibility.

Recall that the directional characteristic of a line of directional sources is known to be the mathematical product of the directional characteristic of a line of point sources with the same arrangement, and the directional characteristic of a single element of that line. Therefore, it is imperative that the size of the transducer not be so large that its inherent directionality limits its usefulness at the upper end of its operating range. If the pattern of the source collapses at too low a frequency, it will be ineffective in integrating with neighboring sources to allow steering in that frequency range. At the same time, it is important that the size of the device be large enough to reproduce low frequencies.

Additionally, steerability is dependant upon source spacing that is proportional to the minimum wavelength reproduced. Assuming the maximum frequency could approach 4 kHz, the ideal source spacing would be around 85 mm.

In contrast, in order to achieve successful pattern control at lower frequencies, a line source length proportional to the maximum wavelength reproduced is necessary.

As with the analysis of the high frequency sources, performance of a single, ideal, continuous, line source was compared to a linear array of sources. In figure 7, the 0°, 15° and 60° off axis responses are displayed for an ideal, continuous, 30° arc source with an included arc of 30°. The polar response displays a well-defined 30° beam, with very little leakage beyond 30° above 500 Hz.
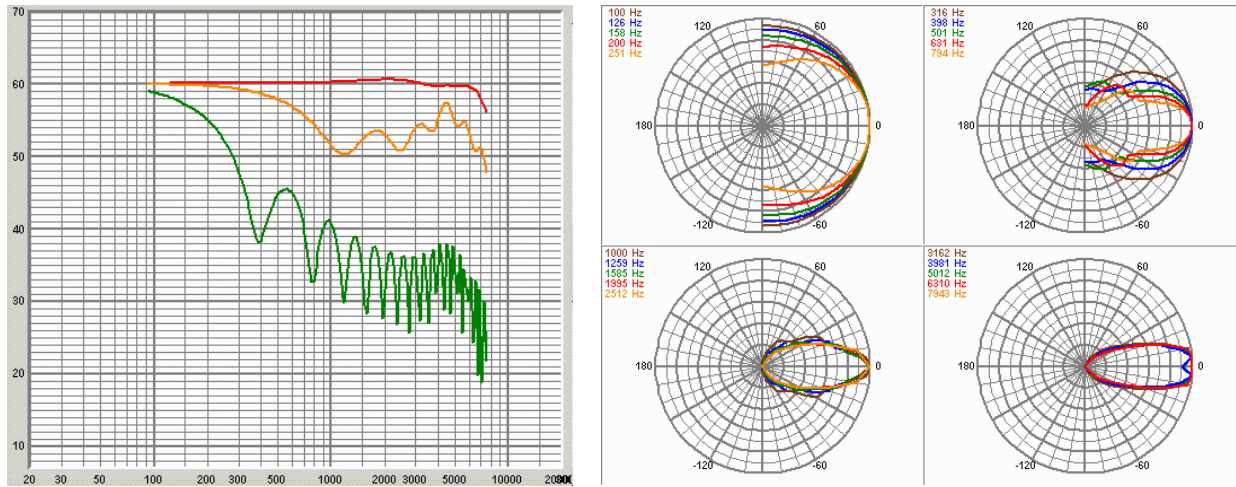

Fig. 7. Ideal, continuous, 30° arc source. Magnitude - Red: 0°, orange: 10°, green: 60°. Polar - 100 Hz to 8 kHz, 1/3 octave.

In figure 8, the 0°, 15°, and 60° off axis responses are displayed for a steered array with the same dimensions as the ideal source, but made up of eight 100 mm cone transducers on 125 mm centers. Both the magnitude and polar responses are very similar to those of the ideal source below 1.25 kHz. However, there is an abrupt deviation from ideal behavior beginning at 2.5 kHz.
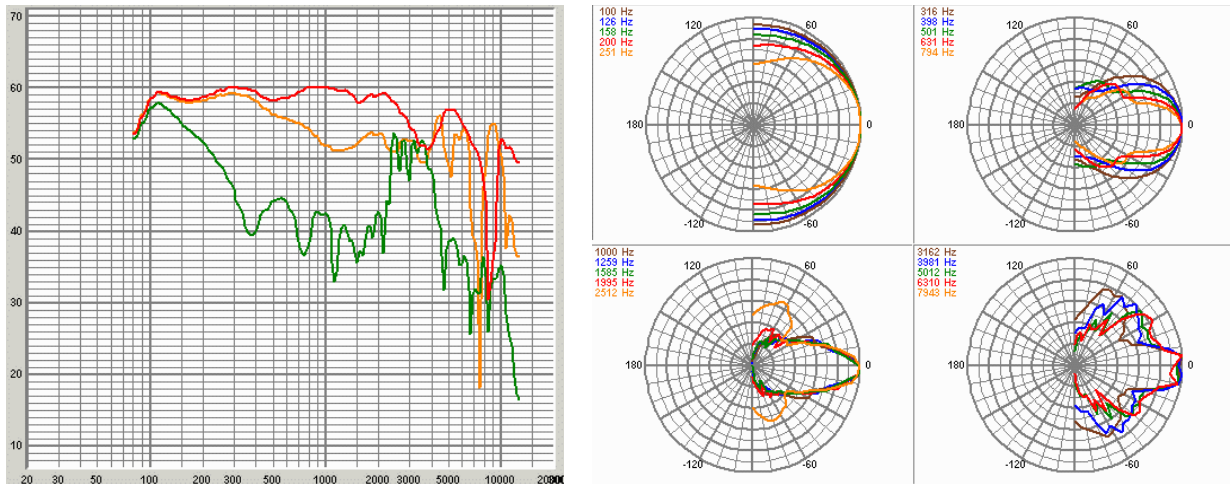
Fig. 8. Array of eight 100 mm cones on 125 mm centers, processed to 30° pattern. Magnitude - Red: 0°, orange: 10°, green: 60°. Polar - 100 Hz to 8 kHz, 1/3 octave.

The reason for this deviation can be understood by inspecting the impulse responses at 60° off axis. Figure 9 shows the 60° off axis response of the ideal source, while figure 10 shows the 60° off axis response of the steered array.
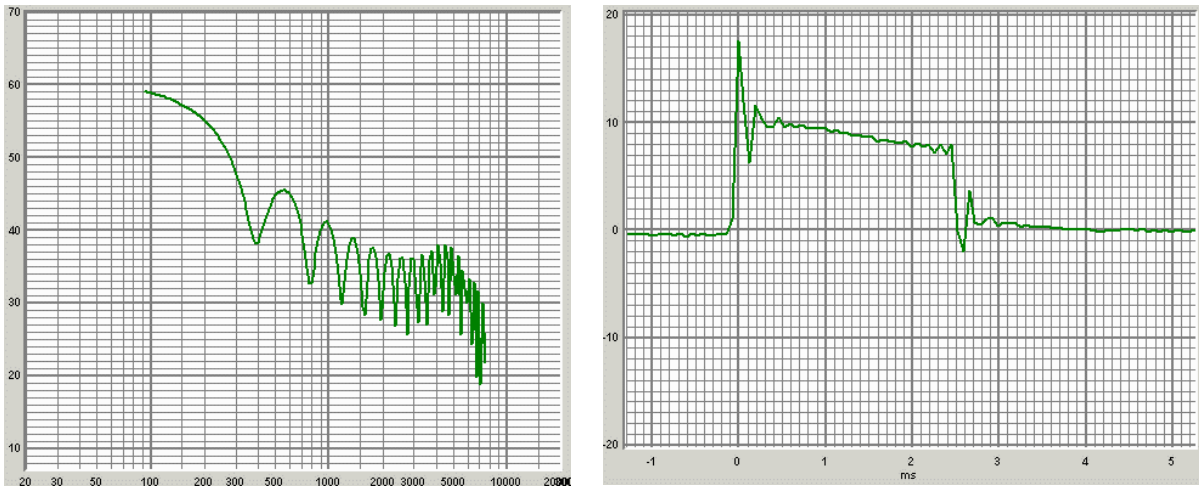

Fig. 9. Response at 60° off axis: ideal, continuous, 30° arc source.

The ideal source exhibits a positive-going pulse corresponding to the nearest edge of the source, a raised portion due to the continuous strength of the source, and finally a negative-going pulse corresponding to the far edge of the source[1].
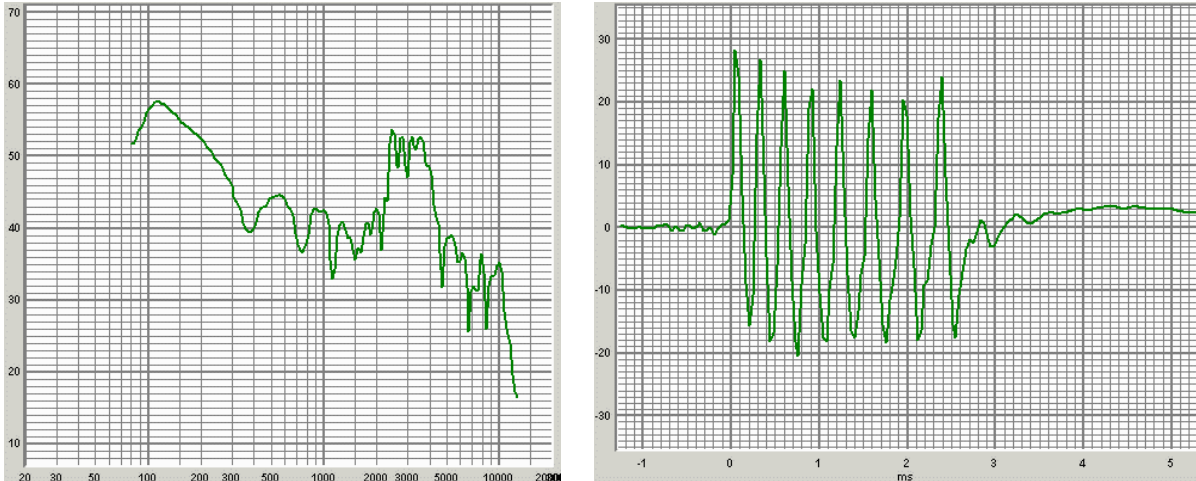
Fig. 10. Response at 60° off axis: array of eight 100 mm cones on 125 mm centers, processed to 30° pattern.

The steered array clearly consists of eight distinct arrivals, each with its own positive going leading edge, and negative-going trailing edge. This straight line of multiple small transducers provides the length necessary to achieve adequate control to 500 Hz; but although the small transducer size should allow for steerability above 2.5 kHz, the spacing of these devices limits their effectiveness in this range.

If the spacing is reduced to 75 mm, the impulse responses of each individual loudspeaker "meld together", with the negative-going, trailing edge of one impulse nearly canceling the positive-going, leading edge of the following impulse. Figure 11 illustrates the magnitude and impulse responses of the same set of sources with their spacing reduced to 75 mm. Note that because the delays applied to the sources approximate a 30° arc, the initial impulses arrive closer together in time than the final ones.
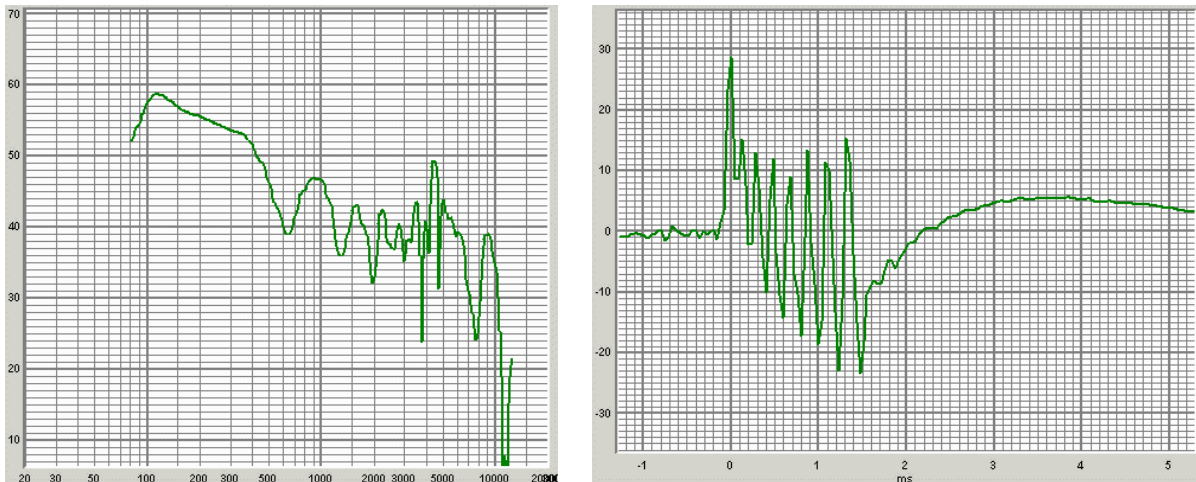

Fig. 11. Response at 60° off axis: array of eight 100 mm cones on 75 mm centers, processed to 30° pattern.

Figure 12 shows that the magnitude and polar responses are much closer to the ideal source than the same set of sources with 125 mm spacing.
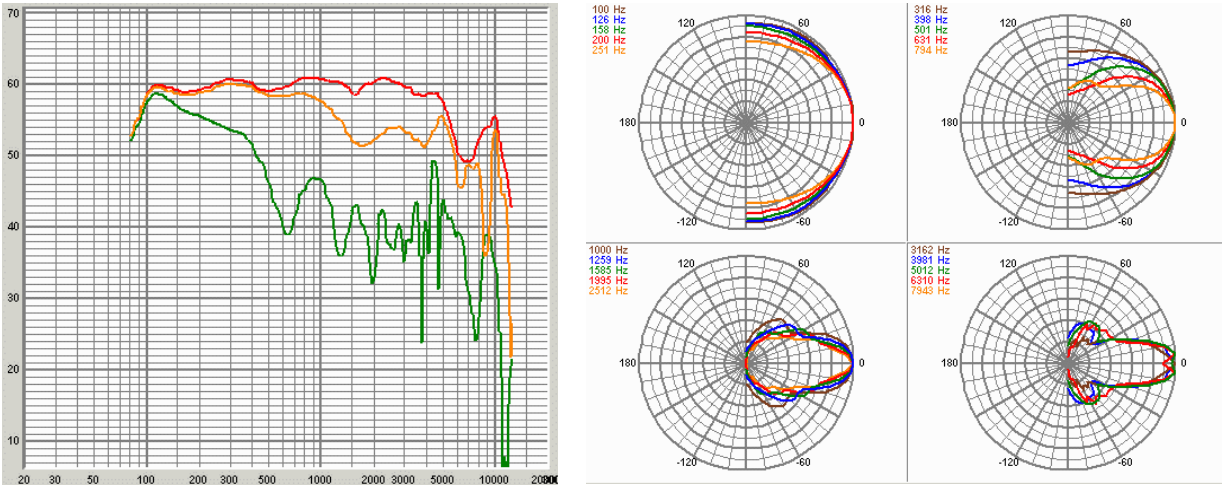
Fig. 12. Array of eight 100 mm cones on 75 mm centers, processed to 30° pattern. Magnitude - Red: 0°, orange: 10°, green: 60°. Polar - 100 Hz to 8 kHz, 1/3 octave.

It might appear that the solution to this problem would be simply to space the transducers 75 mm apart, as modeled here. However, the transducers that produced these results are 100 mm units, with a smallest external dimension and minimum linear spacing of 115 mm.

Fortunately however, a staggered array provides the spacing density required for upper frequency steering. This solution offers the additional benefit of slightly improved control in the horizontal plane, with negligible detriment to the directional results in the vertical plane.

1.3 Implemented Design

The chosen implementation utilizes a high frequency section of eight 25 mm transducers coupled to an edge-to-edge array of horns spaced 41 mm on center. The low frequency section utilizes a staggered array of eight 100 mm cone transducers. Two models currently exist, one utilizing both the high and low frequency arrays, the other containing just the low frequency array. Modular design allows multiple loudspeakers to be combined, allowing the array to be tailored to the specific application. This approach allows longer line lengths to extend pattern control to lower frequencies and/or achieve additional output. The goal of these systems is to perform steering in the vertical plane. Therefore, they are designed for installation flat against a wall in their vertical orientation. Examples are shown in figure 13.

Fig. 13. Examples of digitally steered loudspeaker arrays. Full-range module, low frequency module, multi-enclosure system for extended pattern control.

2 HARDWARE REQUIREMENTS

The loudspeakers shown above contain integral digital signal processing (DSP), amplification, and communications. The techniques used for steering an array of transducers require that each have its own processing and amplification channel. The full-range loudspeaker shown above contains sixteen DSP and amplifier channels, shown in figure 14. Likewise, the low frequency loudspeaker contains eight DSP and amplifier channels.

Each transducer is relatively small. Therefore amplifiers with a relatively low power rating are used. Nonetheless, since sixteen of these amplifiers are used in the case of the full-range model, significant output levels are still possible. Since fan cooling is not desirable for a loudspeaker system, the high efficiency amplifiers utilize the entire aluminum enclosure for convection cooling.

Steering is accomplished via dedicated DSP using a combination of traditional and proprietary digital filters. Crossover functions and user adjustable input parameters such as EQ, delay, gain, and compression are handled with additional DSP.

Control of these DSP parameters, as well as a comprehensive monitoring system, is accomplished via an integrated EIA 485 (RS 485) transceiver. This allows the loudspeaker to be connected to an EIA 485 network for control via a personal computer.

Fig. 14. Block diagram of DSP

3 SOFTWARE REQUIREMENTS

To enable practitioners to realize the full potential of the loudspeaker's digital steering capability, a dedicated software application was created which calculates the required processor settings and applies them to the on-board DSP system.
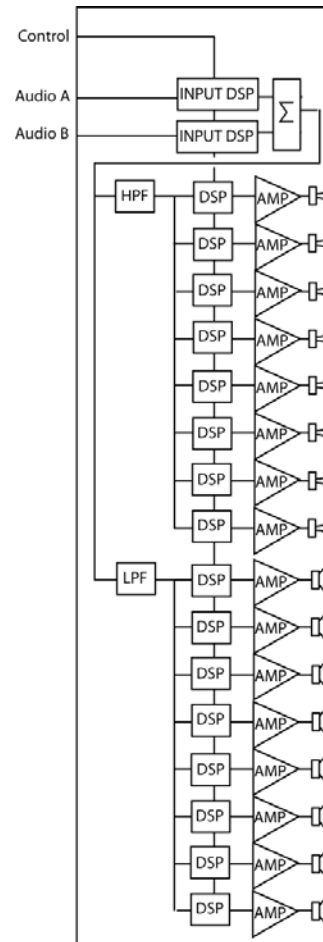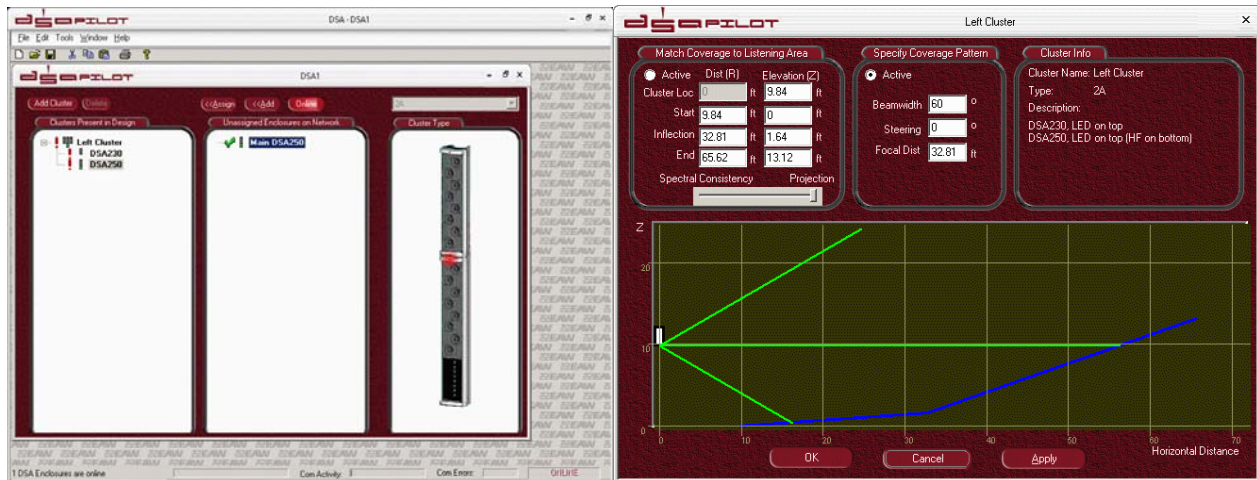
Fig. 15. Software application for controlling digitally steered arrays.

The software displayed in figure 15 allows multiple loudspeakers within a single column to be treated as a single loudspeaker. It is imperative that the type, position, and orientation of each loudspeaker used in the column are properly communicated to the software. Once this is done, DSP parameters are applied to all loudspeakers within the column simultaneously. Thus, the entire length of the columnar array is used to provide the best coverage possible based on the user's input. Once a specific pattern and steering angle is specified, DSP parameters are calculated by the software on the PC and uploaded to the loudspeaker. Alternatively, specific venue information can be entered, allowing the software to calculate the DSP parameters to form a more "complex" pattern to better suit the listening area. Regardless, a combination of direct calculation and iterative optimization establishes the correct DSP settings. This is detailed in "Practical Benefits & Limitations of Digitally Steered Arrays" by David W. Gunness and William R. Hoy[2].

4 PERFORMANCE LIMITS

The modular approach detailed above has the drawback of introducing physically larger gaps between adjacent transducers (between loudspeakers) than exist within a single loudspeaker. However, these gaps are kept to a minimum and have such negligible effects on the system's performance that they are insignificant considering the benefits of a modular and scalable design.

Limits also exist for narrow patterns in the low frequency range. Figures 16 and 17 illustrate the benefit of a longer line of transducers. Each of the loudspeaker arrays depicted was processed to form a 20° beam. Note the exceptional control of the longer array. The short array will provide excellent control at higher frequencies, but cannot match the performance of the longer array in the lowest octaves.
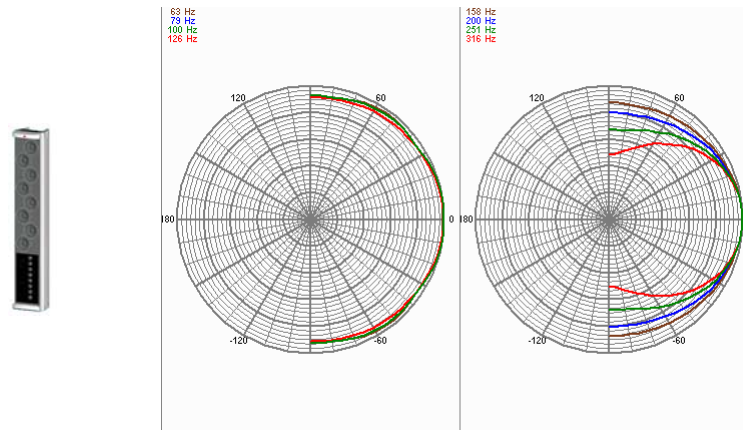
Fig. 16. Polar response of a digitally steered loudspeaker array. Processed to 20° beam, 80 Hz - 315 Hz, 1/3 octave.
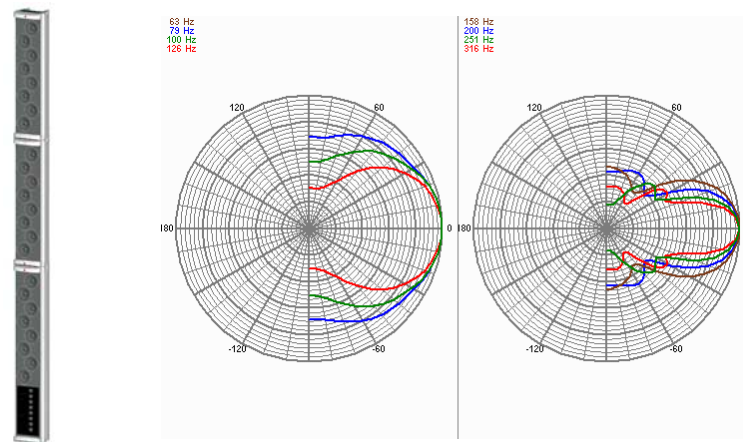

Fig. 17. Polar response of three digitally steered loudspeaker arrays. Processed to 20° beam, 80 Hz - 315 Hz, 1/3 octave.

Two methods for defining coverage were briefly discussed above. The traditional approach is to define a pattern, steering angle, and focal distance. The focal distance is the area in space where the output from the low frequency and high frequency sections converge[2]. Figure 18 illustrates the advantages of the more comprehensive method that matches the coverage pattern to the listening area based on room dimensions. The polar responses shown are from the same steered array, its coverage pattern defined by the two methods. The polar response on the left is derived via the traditional method while the polar response on the right is derived from the listening area matching method.

Note the reduction in grating lobes between 1 kHz and 2.5 kHz when the listening area matching method is used. Also note that above 2.5 kHz, the pattern is much more consistent.
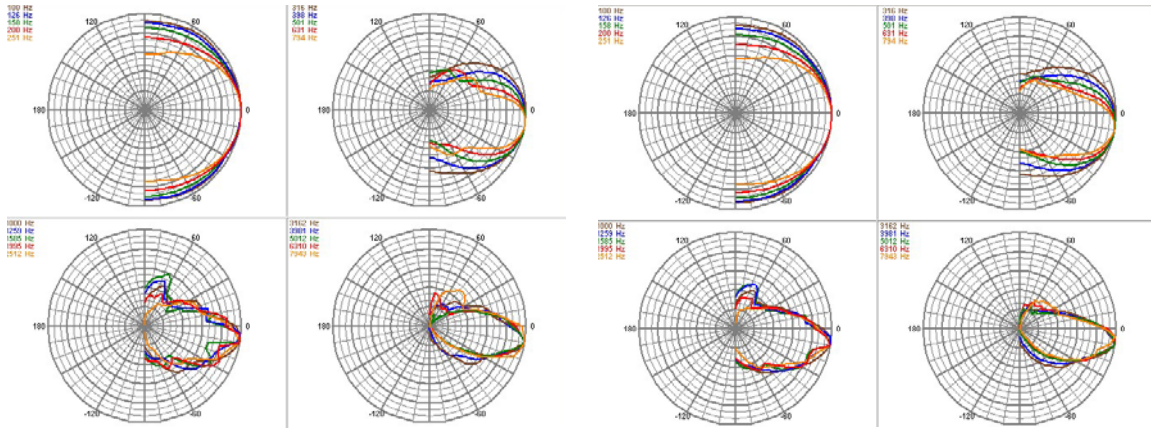
Fig. 18. Polar response, 100 Hz – 8 kHz, 1/3 octave. Left - traditional method, right – listening area matching method.

Further discussion of the limitations of this technique, specifically steering limits and pattern control limits, are detailed in "Practical Benefits & Limitations of Digitally Steered Arrays" by David W. Gunness and William R. Hoy[2].

5 CONCLUSION

The requirements for successfully steering a wide-bandwidth array of transducers and an implementation thereof were described. This two-way implementation specifies a high frequency section of small transducers coupled to an edge-to-edge array of tightly spaced horns. The low frequency section requires a staggered array of small cone transducers.

Details of the internal hardware were presented. The number of processing and amplifier channels required for a digitally steered array necessitates integral electronics. This significantly simplifies use and setup. Communication circuitry for control of DSP parameters and monitoring is also described.

A software interface was presented. It calculates DSP settings for proper beam forming and steering based on user-supplied information. Two methods of defining the beam pattern were presented. Data shows that utilizing the DSP to form a complex beam that matches the coverage to the listening area provides better results than the traditional method.

6 REFERENCES

[1] D. W. Gunness and R. Mihelich, "Loudspeaker Acoustic Field Calculations with Application to Directional Response Measurement", presented at the 109th Convention of the Audio Engineering Society, 2000

[2] D. W. Gunness and W. R. Hoy, "Practical Benefits & Limitations of Digitally Steered Arrays", presented at the 115th Convention of the Audio Engineering Society, 2003