Meyer Sound

TECHNICAL REPORT

DSP Beam Steering with Modern Line Arrays

There are two ways to aim the sound of modern, high-powered loudspeakers: physically and "virtually."

Physically aiming loudspeakers is straightforward – you point the loudspeakers where you want the sound to go. However, as professional sound designers know, loudspeakers are not like flashlights and sound does not behave like light; loudspeakers don't create perfect spotlights of sound at all frequencies. And unlike light, the sound from two different loudspeakers aimed at the same location can create audible phase cancellations and combing. (Actually, light from two different instruments creates cancellations as well, but the speed of light is so fast and the wavelengths are so small that our eyes can't see the cancellations).

Virtually aiming loudspeakers is more complicated. Because sound waves from different loudspeakers can both combine or cancel depending on the relative phase relationships between the sound waves, it is possible to manipulate the phase (and magnitude) of the sound from two or more loudspeakers to control where the sound cancels and where the sound sums. Each frequency has a different wavelength, so the phase of each frequency has to be controlled independently to allow each frequency to sum and cancel in the right place. Manipulating the magnitude and phase of every loudspeaker in an array of loudspeakers is commonly referred to as "beam steering." Since every loudspeaker in the array must be controlled individually, it is impractical to beam steer with analog filter sets. However, over the past few decades, digital signal processors (DSPs) have become available at a reasonable cost. This forces the question: "Now that it is possible to individually control the magnitude and phase of every loudspeaker in an array, is this useful?"

Since DSPs have only recently become inexpensive enough for widespread professional audio usage, there are very few books or articles describing how to beam steer loudspeakers. However, the military has been using beam steering techniques in two main areas: antenna arrays (radar) and underwater arrays (sonar). The military has also had access to DSPs for much longer than audio professionals, and so for this reason the main references and ideas for audio beam steering come mainly from textbooks about antenna theory and underwater acoustic sonar.

There are three main reasons why beam steering loudspeakers using examples from antenna theory or sonar can have unintended consequences: (1) Eleven Octaves, (2) Waveguides / Horns, and (3) Back Lobes.

Eleven Octaves (Small Wavelengths to Large Wavelengths)

Beam steering loudspeakers is more difficult, as compared to antenna theory or sonar, primarily as a result of the remarkable frequency span of the human ear. Human hearing ranges from approximately 20 Hz (low frequencies) to 20 kHz (high frequencies). The wavelength of a pure tone at 20 Hz is approximately 50 feet (15.25 meters); the wavelength of a pure tone at 20 kHz is one-half inch (13 millimeters). This 11-octave frequency range makes beam steering difficult. Usually, antenna arrays and sonar arrays work only for a single octave at most, and often only at a single frequency. Therefore, the array spacing and geometry can be tailored to produce a beam. In fact, it is often the case that different arrays are optimized and used for different frequency bands. This would be impractical for most professional loudspeaker applications. Generally, it is necessary for the size of the array to be larger than a wavelength for beam steering to work. To steer low frequencies you would need hundreds of loudspeakers. However, element spacing is also critical, so the hundreds of loudspeakers needed to steer low frequencies would be spaced sub-optimally for the mid and high frequencies. This wide range of wavelengths makes beam steering applications for professional audio applications even more difficult, no matter that the DSP power is available to control the individual magnitude and phase of each individual loudspeaker at every frequency.

Waveguides and Horns

Waveguides and horns are used to direct sound in a particular manner. Waveguides and horns are conceptually the same – physical devices that bounce sound around to aim it differently than where it would otherwise have gone. Horns and waveguides are used extensively in loudspeakers. Unfortunately, they make beam steering difficult if not sometimes impossible. In order for beam steering to work, the sound radiated from one loudspeaker needs to be influenced by the sound from other loudspeakers comprising an array. If the sound from two (or more) loudspeakers does not overlap, the sound CANNOT be steered.

And why does this matter? Modern line arrays might look like closely spaced elements – which look like diagrams from books on antenna theory or audio textbooks that use equally spaced theoretical omnidirectional sources to illustrate examples of beam steering – but they are actually VERY DIFFERENT.

All modern line arrays use a combination of direct radiating low- and sometimes mid - frequency transducers and waveguides coupled to compression drivers to produce high frequencies.

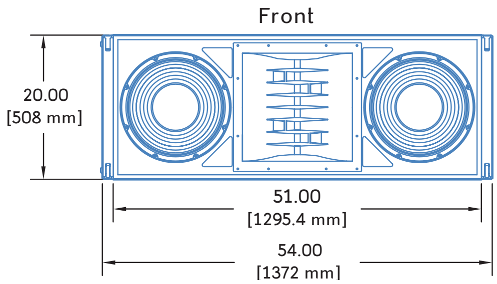

Figure 1

For example, the Meyer Sound M3D Line Array loudspeaker (Figure 1) uses a waveguide (the Meyer Sound REM ribbon emulation manifold) coupled to two 4-inch diaphragm / 1.5-inch exit compression drivers to reproduce high frequencies. This design produces a very narrow vertical polar pattern and a very wide horizontal polar pattern.

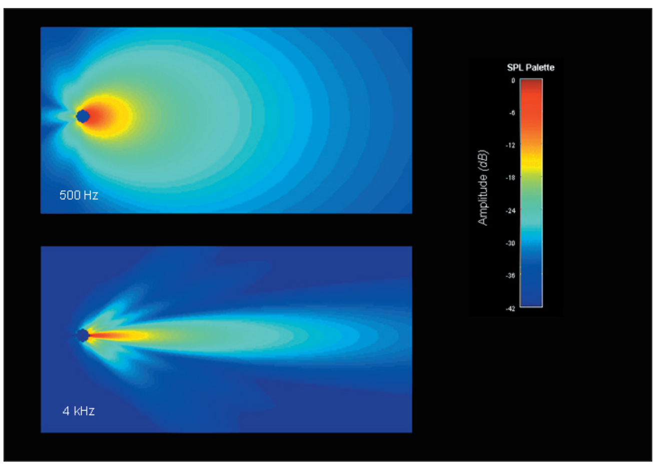

Figure 2

These images from Meyer Sound's MAPP (Multipurpose Acoustical Prediction Program) Online (Figure 2) show the sound field prediction of one M3D element at 500 Hz and 4 kHz, which correspond to a vertical polar pattern (averaged over one octave).

At 500 Hz, while not omnidirectional, the coverage pattern is wide enough for beam steering to work. At 4 kHz, the M3D creates an extremely narrow (approximately 10° vertical) beam.

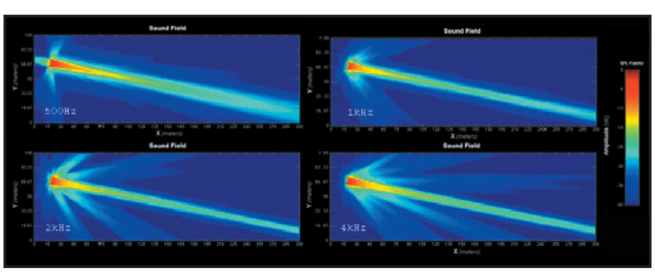

Figure 3

When multiple M3D elements are used, the coverage pattern is uniform. The low frequencies become directional due to line array theory, and then match the narrow high-frequency beam created by the REM. Sixteen M3Ds physically tilted down create a tight, narrow acoustic field at both low and high frequencies (Figure 3).

General criteria for successful beam steering:

- Omnidirectional or nearly omnidirectional sources
- Inter-element spacing less than one half the wavelength of the highest frequency
- Total length greater than the wavelength of the lowest frequency
- Enough DSP filters to control each element's phase and magnitude

The M3D elements meet these criteria for beam steering below 500 Hz, while they fail to meet these criteria above 500 Hz. Consequently, it is NOT possible to beam steer the high frequencies of an M3D array.

So what happens when you apply a simple beam steering algorithm to a hybrid line array? The results are fascinating and discouraging, as the MAPP Online predictions in Figure 4 show. MAPP Online can accurately predict the acoustic summing and phase cancellations of loudspeakers and does this by taking phase into account when predicting the interaction.

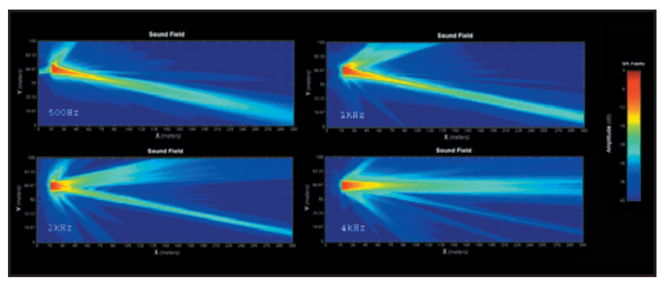

Figure 4

The above MAPP Online predictions show the result of sixteen M3Ds steered downward with a different length delay applied to each element. This creates a beam that is steered down by 20° (Figure 4). At 500 Hz, the beam steering essentially works and the acoustic field is steered down by using DSP. The delay applied to each M3D element changes the relative phase of each of the 16 elements and the sound cancels in front of the array but sums in phase 20° down.

However, the delay creates unwanted sound paths for the high frequencies. At 1 kHz there is a downward beam, but a lot of energy is also being directed UP. These phenomena are known as "grating lobes" and they occur when the element separation becomes too large compared to the wavelength. The description of how and when they occur is beyond the scope of this paper.

At 2 kHz and 4 kHz the delay has no effect on the direction of the main sound beam. The single M3D element polar patterns at these frequencies do not overlap, and consequently it is impossible to change the direction of the sound. If delay beam steering is applied in actual practice to 16 M3Ds the sound field is scrambled. The low-frequency beam separates from the high-frequency beam. Beam steering M3Ds (or any modern line array) simply doesn't work. In fact, no filters that exist could steer an M3D array above 2 kHz. Even in a line array where the high frequencies are produced by a ribbon driver, the frequencies above 2 kHz would not be steerable since the length of the ribbon driver would be too great (2 to 4 inches) as compared to the wavelength of high frequency sound (10 kHz has a wavelength of 1 inch).

The Problem of Back Lobes

Even if an array of transducers meets the four criteria for successful beam steering, there is another problem. Unlike with physical steering, virtual beam steering can have unintended and unintuitive consequences.

Imagine an array of 16 12-inch woofers arrayed in a line. This hypothetical loudspeaker system has no horns. And we will only use the transducers in the range where they are nearly omnidirectional (below 1 kHz). Instead of physically tilting this array, we will use DSP beam steering to create a downward beam at 20°. Unlike the result when physically tilting the array down, the sound coming off the back of the array is ALSO steered down, worsening the situation. The sound is steered down in a cone shape. So if the array were hanging near a stage, the beam would steer down not only toward the audience but directly onto the stage as well.

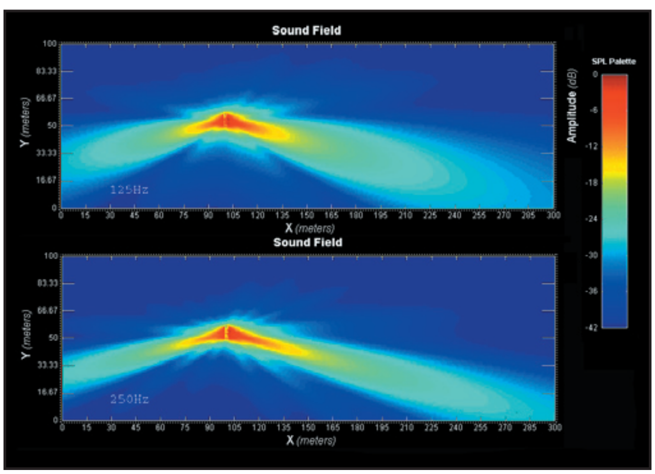

Figure 5

These MAPP Online sound field plots show a stack of 12 inch woofers beam steered using delay for 125 Hz, 250 Hz, 500 Hz and 1 kHz (Figures 5 and 6).

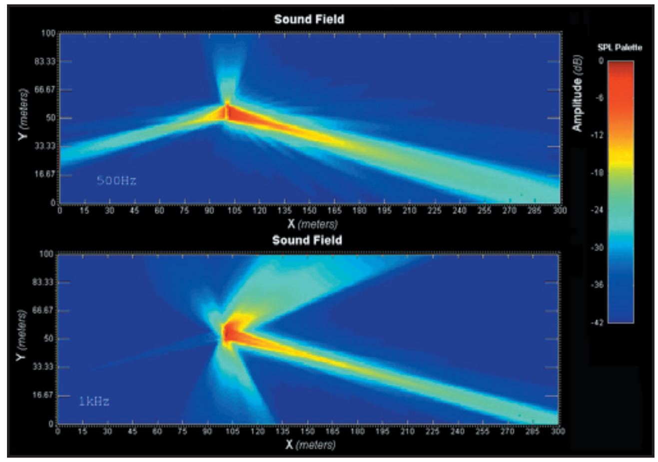

Figure 6

These MAPP Online sound field images show successful beam steering in the forward direction. However, at 125 Hz, 250 Hz and 500 Hz, there is a very strong rear-facing lobe almost equal in strength to the forward-facing beam. Beam steering does not virtually "tilt" the array – instead it turns a circular disk of sound into a 3D cone of sound. At 500 Hz there is not only a back lobe, but a lobe (sound beam) pointing upward. By 1 kHz, the rear beam has disappeared. These are "grating lobes" and their behavior is complicated.

Since it is hard to visualize three-dimensional sound fields on a two-dimensional screen, the following examples show a three-dimensional rendering of this cone-shaped sound field. The first image (Figure 7) corresponds to the MAPP Online sound field image. The second image (Figure 8) shows the cone of sound tilted upwards for easier viewing.

These 3D visualizations were created by using the software program Sysnoise.

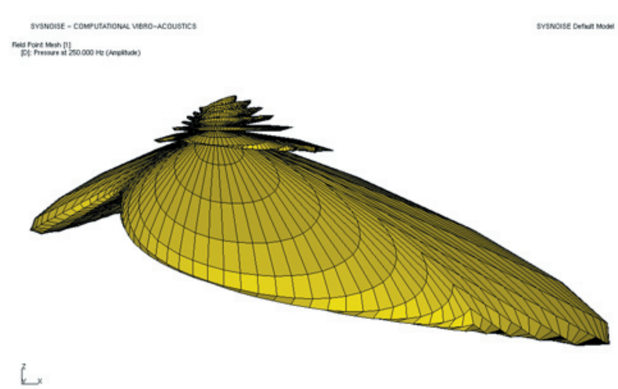

Figure 7

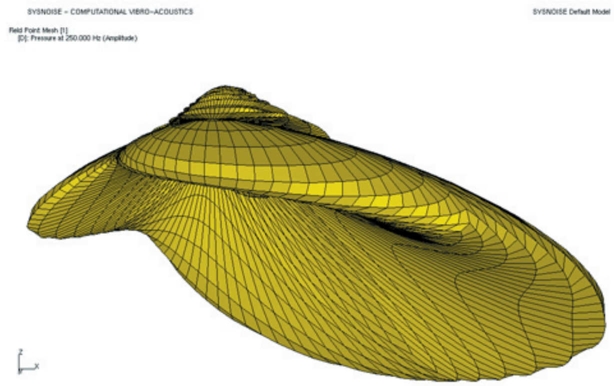

Figure 8

Conclusion

In this technical report, we have shown that even simple beam steering experiments can have unintended and unwanted consequences when applied to modern loudspeaker arrays. We have demonstrated the differences between physically steering loudspeakers and beam steering loudspeakers. The main problems were identified: the 11 octave wide range of human hearing, the near impossibility of steering the sound produced from specialty waveguides, and the unintuitive back lobes and the cone of sound. We are not claiming that in all circumstances beam steering is wrong – only that the design must be carefully modeled with an understanding of the consequences.

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