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Loudspeaker Array Low-Frequency Pattern Control using Filtered Array Technology™

1: Overview

Array directivity control theory is not new. Olson's *Acoustical Engineering* in 1940 discussed Gradient microphone arrays, and both it and Beranekís 1954 Acoustics have sections on line arrays. In the 1970s JBL offered two tapered and shaded line array systems, the 4375 and 4380 designed by George Augspuger. David Klepper, Topper Sowden, and others have used sophisticated line array designs for installed sound reinforcement system for several years.

Low cost DSP that conveniently provides the signal processing required for low frequency control, coupled with customer requirements dictating smaller arrays with tighter pattern control, has renewed interest in the concept. Simulation software aided design has further stimulated manufactures to offer solutions to the market.

JBL researched several approaches to controlling the low frequency pattern, including constructing full size arrays for proof of concept. Three of the most useful designs are presented here. Two are Halfwave Line Arrays, which provide good attenuation at 90∞ off-axis and propagate radiation into the audience area with half the rate of attenuation of a non "steered" cluster. That is, because of the directivity characteristics of the array SPL drops 3 dB with doubling of distance, not 6 dB. This provides more even coverage from front to back at low frequencies, previously a difficult problem. The third cluster is a Gradient Array. It uses a steering element behind the main cluster to null the main clusterís radiation directly below it. This can be very useful in houses of worship and other applications using lavalier or podium microphones located underneath the cluster. One other important advantage of this design is its compactness.

Section 2 of this paper describes how constructive interference works to provide pattern control and Section 3 details the cluster components, construction, signal processing parameters, and expected results.

2: Demonstration of Principle

In this section we will use very small loudspeakers to demonstrate interference concepts, and how they can be used for directivity control. The loudspeaker used is about one third the size of what would be used for sound reinforcement. Therefore the effects can be scaled in frequency: what occurs at 300 Hz in the model will be at 100 Hz for a cluster three times as large.

When two sound sources producing identical program are displaced relative to each other, they will combine to produce a unique interference pattern that depends on the observerís location. The interference pattern is a result of the different arrival times from the two sources. For a position directly on the common axis of the two sources, and equal distance from each of them, the relative combined response will simply be +6 dB louder than that of a single source alone. This is known as coherent summation of two signals. They are identical in phase and amplitude at all frequencies and thus combine to +6 dB.

Figure 1 shows what occurs when an observer moves slightly off-axis of two sources. This example illustrates two different positions, the first position creates a condition where the path length difference results in a time displacement of 0.25 ms, the second 1 ms. The 0.25 ms difference will result in an apparent 180° phase shift for the frequency of 2 kHz and an apparent phase shift of 360° at 4 kHz. The frequency dependent phase shift introduced by the relative displacement of the two sound sources means that the sound cancels starting at 2 kHz, is reinforced at 4 kHz, cancels at 6 kHz, and so on every 2 kHz. This type of response is known as comb filtering because of its resulting frequency response. If the resulting displacement were 1 ms, then the fundamental cancellation is at 500 Hz, with summation and cancellation intervals of 500 Hz.

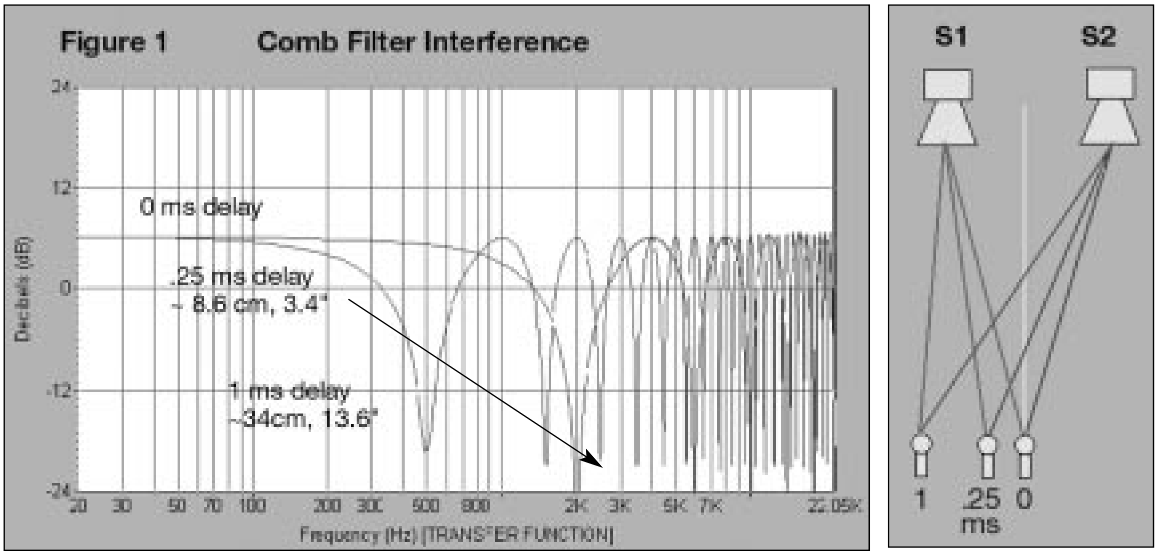


Figure 1 Comb Filter Interference

The interference (comb filtering response) occurring in an array of loudspeakers can be used to our advantage for directivity control. Figure 2 is an example of four loudspeakers placed in a line with a 23.5-cm (9.25") spacing, without filtering.

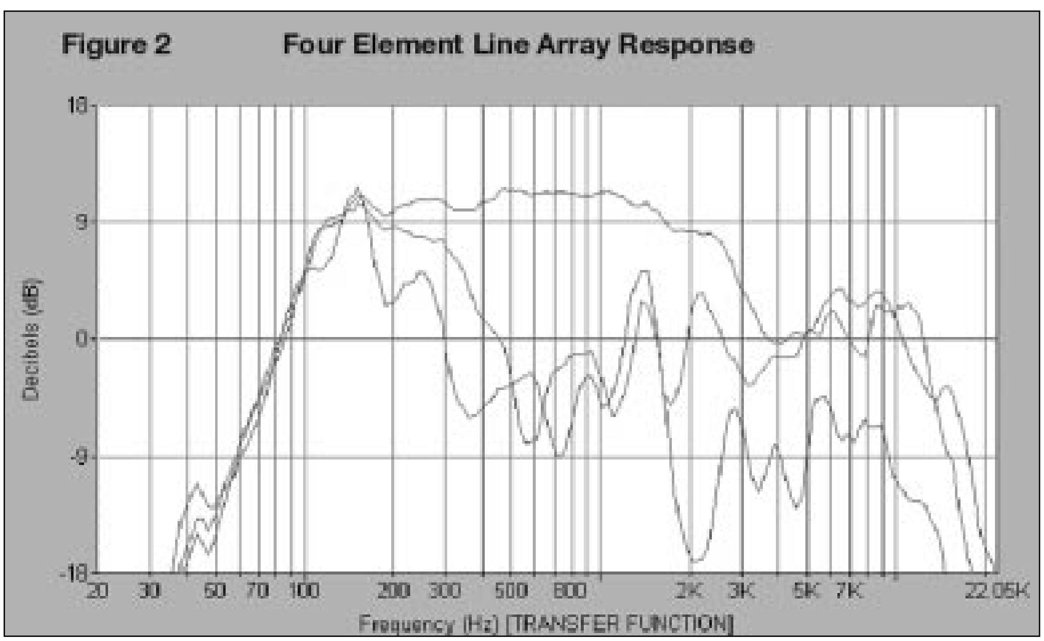
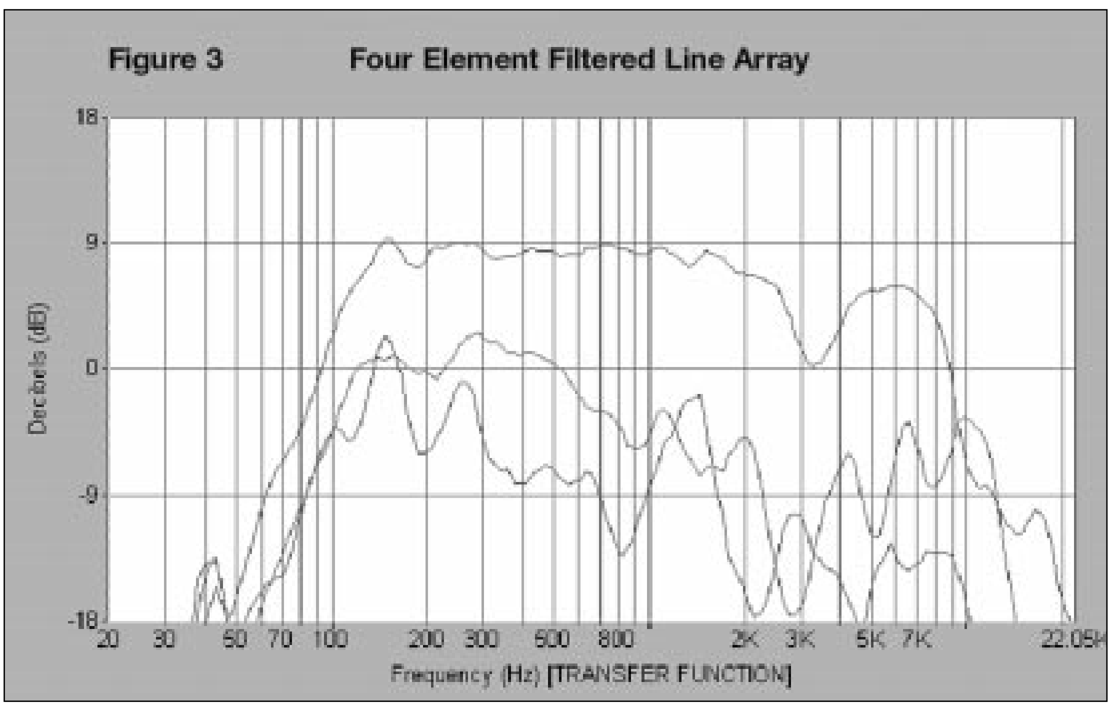


Figure 2 Four Element Line Array Response

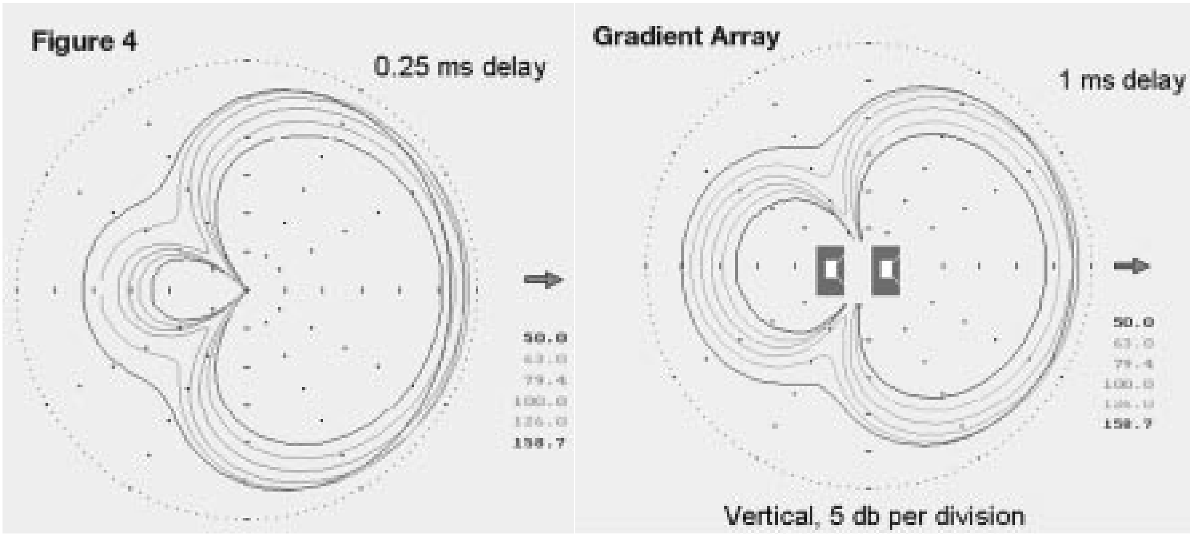
Here is the on-axis, 45°off-axis, and 90° off-axis response of a four element line array. The on-axis level goes up by +12 dB relative to a single element, and the

90° axis attenuation is increased to as much as 15 dB in the 400 Hz to 800 Hz octave band. However, the response is not uniform and would have an annoying sound due to the peak in the response at 1.6 kHz. Summation of elements 4 and 1 create a primary interference notch in the 200 Hz to 300 Hz band. This would be expected because the spacing of the loudspeakers produces a 1.4 ms delay between the sound arrivals at the 90° off axis position. Each pair of loudspeakers will produce its own comb filter response that can be used for pattern control. Summation of elements 4 and 2 create a primary interference notch in the 400 Hz region, elements 4 and 3 in the 800 Hz region.
If we use a set of bandpass filters on the array elements so that each pair is operated only over their primary notch bandpass, we could smooth the off axis response.

Figure 3 shows the result of applying bandpass filters to a four-element system. Element 1 is operated full range, Element 2 is operated only in the octave about 750 Hz, Element 3 the octave about 273 Hz, element 4 the octave about 215 Hz. The 90° off axis attenuation is now nearly 14 dB across a wide bandwidth with a smoother response. The 45° response is about 10 dB down and exhibits smooth response. Note the trade off for this array to the typical line source is that the maximum on axis level is 3 dB down from the driving all array elements full range.



A gradient array is very useful in that it allows the designer to “tune” the attenuation null. The simulation in Figure 4 shows how varying the delay to the steering element moves the null.



A full range loudspeaker or a cluster of loudspeakers is arranged in front of a “steering element”. The steering element is driven over a limited bandwidth of ~150 Hz, at -6 dB from the main speaker, with inverted polarity. The front element(s) have signal delay, the amount of delay determines the null location. Construction of this array can be very compact requiring an envelope as small as one cubic foot. An array capable of a medium size house of worship requires only cube three feet per side.

Section 3: Practical Implementations of Filtered Array Technology

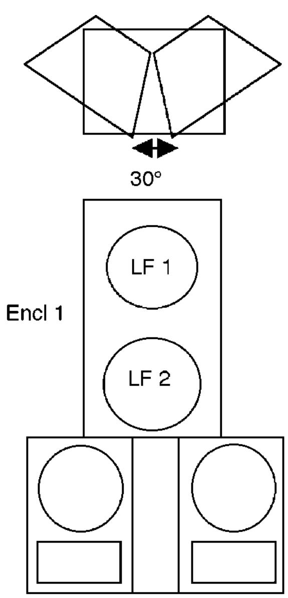
This section describes three arrays; a Three Element Bandpass, a Four Element Bandpass, and a Gradient. Information on construction, signal processing and performance is given for each array. JBL Sound Power model loudspeakers, their arrangement, and DSC260 signal processing parameters are presented. On-axis, 45° and 90° off-axis frequency response curves are also included. The response curves provide both the best method to evaluate the arrayís suitability for use with open microphones, and a convenient performance verification check requiring only three measurements.
Please note rear wall and ceiling reflections will interfere with pattern control. It is recommended that the cluster be at least 20 feet from rear wall and 10 feet from ceiling. The gradient array can be mounted directly against the ceiling, or be spaced a minimum of 10 feet away.

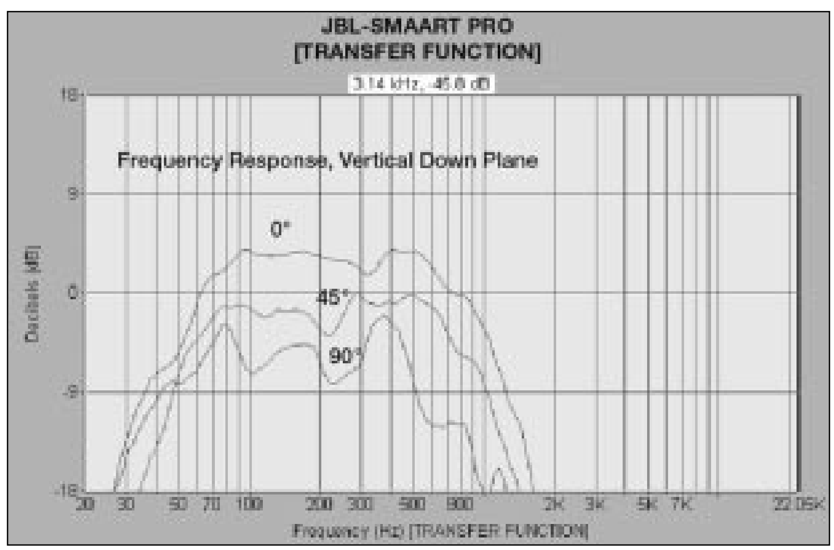
3 Element Bandpass Array

This simple array combines moderate under cluster attenuation with uniform coverage to the rear of the room. The example shown provides 120° horizontal coverage but other loudspeakers can be used to cover as narrow as 60°, or up to 360° of horizontal coverage. When using other configurations, care should be taken to balance the output of both low frequency steering elements with the clusterís output to maintain desired coverage.

Coverage Angles: 120° Horizontal x 50° Vertical (For Array Shown)
Under Cluster Attenuation: > 6 dB
Cluster Configuration: 2 Unit Arc + Vertical Low Frequency Pair
Array Elements: 2 x SP215-6 + 1 x SP215S
Signal Processing: 1 x DSC260
Amplifiers: 4 Channels, 2 x MPX600

Signal Processing Parameters														
Amplifier		Element		Steering Filters					Eq Filters					
#	Ch	Encl	Trans	Gain dB	Delay ms	Polarity	Lo Slope dB / Type / Freq	Hi Slope dB / Type / Freq	Type Bdw	Freq Hz	Gain dB	Type Bdw	Freq Hz	Gain dB
1	A	1	LF 1	-3	0.27	Norm	12 / But / 36	12 / LR / 189						
1	B	1	LF 2	-15	0.27	Norm	12 / But / 36	18 / But / 1.14k	0.8	210	8			
2	A	2, 3	LF	0	0.27	Norm	12 / But / 46	24 / LR / 1.14k	0.3	1k	-2			
2	B	2,3	HF	-8	0	Norm	24 / LR / 1.14k	Out	Hi12	8.28k	5	0.45	3.48k	-2





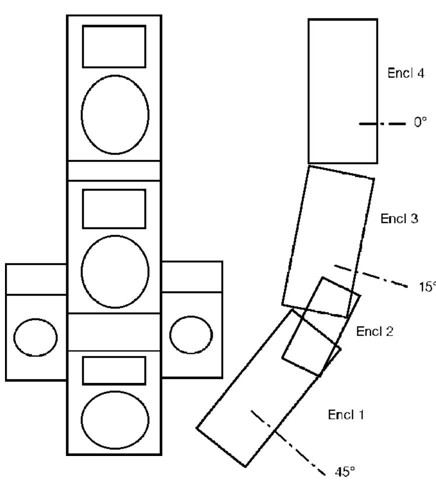
4 Element Bandpass Array

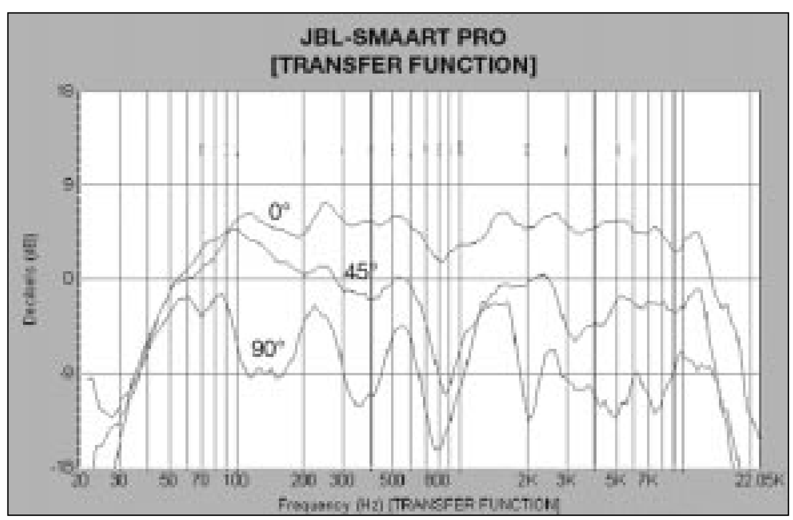
This more complex array combines moderate under cluster attenuation with very uniform coverage to the rear of the room. The example shown provides 60° horizontal coverage by 95° vertical but other loudspeakers can be used to cover wider than 60° of horizontal coverage. When using other configurations, care should be taken to balance the output of both low frequency steering elements with the clusterís output to maintain desired coverage.

Coverage Angles: 60° Horizontal x 95° Vertical
Under Cluster Attenuation: > 6 dB
Cluster Configuration: 3 Element Arc + Side Low Frequency Pair
Array Elements: 3 x SP215-6 + 2 x CSP115 (Custom Shop Model)
Signal Processing: 1 x DSC260
Amplifiers: 6 Channels, 2 x MPX1100, 4 x MPX600

Signal Processing Parameters

Amplifier		Element		Steering Filters					Eq Filters					
#	Ch	Encl	Trans	Gain dB	Delay ms	Polarity	Lo Slope dB / Type / Freq	Hi Slope dB / Type / Freq	Type Bdw	Freq Hz	Gain dB	Type Bdw	Freq Hz	Gain dB
1	A	1	LF	0	0.021	Norm	12 / But / 46	12/ LR / 138						
1	B	2	LF	0	0.896	Norm	12 / LR / 500	12 / LR / 1k						
2	A	3	LF	-15	0.979	Norm	12 / But / 46	24 / LR / 1.14k	1	241	6	Hi12	615	-10
2	B	4	LF	0	0	Norm	12 / But / 46	24 / LR / 1k						
3	A	1	HF	-7	1.313	Norm	24 / LR / 3k	Out	Hi12	8.28k	5			
3	B	3, 4	HF	-4	0.542	Norm	24 / LR / 1k	Out	Hi12	8.28k	5			





Gradient Array

This very simple array provides greater than 10 dB under cluster attenuation with control of null location and very uniform off-axis frequency response. The example shown provides 120° horizontal coverage by 50° vertical but other loudspeakers can be used to provide up to 360° of horizontal coverage. When using other configurations, care should be taken to balance the output of both low frequency steering elements with the clusterís output to maintain desired coverage.

Coverage Angles: 120° Horizontal x 50° Vertical
Under Cluster Attenuation:> 10 dB
Cluster Configuration: 2 Element Arc + Rear Steering Element
Array Elements: 2 x SP215-6 + 1 x CSP115 (Custom Shop Model)
Signal Processing: 1 x DSC260
Amplifiers: 3 Channels, 1 x MPX1100, 1 x MPX600

Signal Processing Parameters																	
Amplifier		Element		Steering Filters								Eq Filters					
#	Ch	Encl	Trans	Gain	Delay	Type	Polarity	HP Slope	LP Slope	Type	Freq	Gain	Type	Freq	Gain
				dB	ms			dB / Type / Freq	dB / Type / Freq	Bdw	Hz	dB	Bdw	Hz	dB
1	A	1, 2	LF	0	0.88	BP	Norm	12 / But / 46	24 / LR / 1.14k						
1	B	1, 2	HF	-8	2.48	HP	Norm	24 / LR / 1.14k	Out	Hi12	8.28k	5	0.45	3.5k	-2
2	A	3	LF	-6	0.271	BP	Invert	12 / But / 46	12 / But / 148