Presented at the 32nd AES Conference, 2007 September 21-23, 2007, Hillerod, Denmark

Application of Linear-Phase Digital Crossover Filters to Pair-Wise Symmetric Multi-Way Loudspeakers Part 2: Control of Beamwidth and Polar Shape

D. B. (DON) KEELE, JR.

Harman/Becker Automotive Systems, Martinsville, Indiana, USA

ULRICH HORBACH

Harman Consumer Group, Northridge, California, USA

Introduction

In part 2, we simplify the design process and emphasize beamwidth and polar shape of the array.

We do this by restricting the level of the forced-to-be-flat off-axis angle to -6 dB.

This forces the beamwidth of the array to be flat and with appropriate selection of driver spacing, makes the polar patterns fairly uniform as well.

Outline

- Polar Pattern of Two Separated Point Sources
  - Beamwidth
  - Side-lobe level
- Linear Combination of Patterns of Two Pairs of Separated Point Sources
  - Summing ratios
  - Consistency of off-axis response
- Calculation of Crossover Frequency Responses
  - Four sources: Two pairs of sources
  - Three sources: A single pair of sources with a single central source
- Five-way Design Example
  - Front panel design
  - Crossover responses
  - Beamwidth and directivity
- Summary

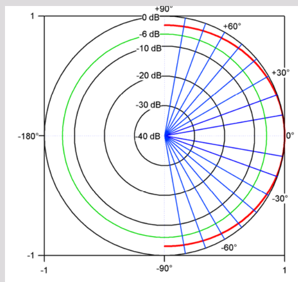
harman international

harman consumer group

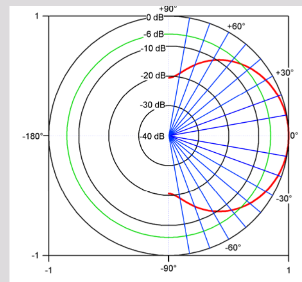
HARMAN/BECKER AUTOMOTIVE SYSTEMS

Frontal Polar Pattern of Two Separated Point Sources Versus Wavelength Spacing

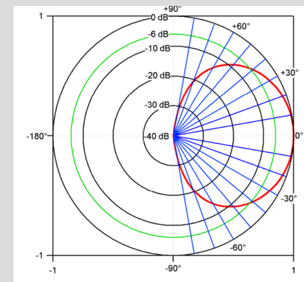
D/λ = 0.1,
Beamwidth = 180º



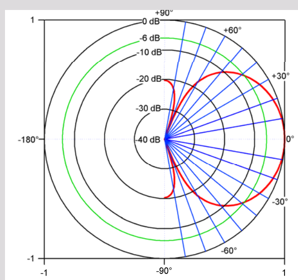
D/λ = 0.47,
Beamwidth = 90º



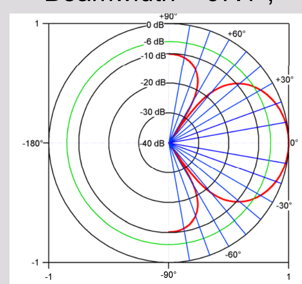
D/λ = 0.5,
Beamwidth = 83.6º



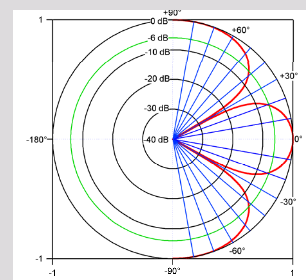
D/λ = 0.53,
Beamwidth = 77.5º



D/λ = 0.6,
Beamwidth = 67.1º,

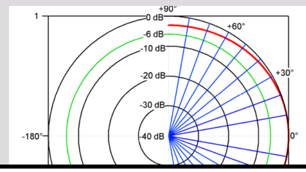


D/λ = 1,
Beamwidth = 38.7º

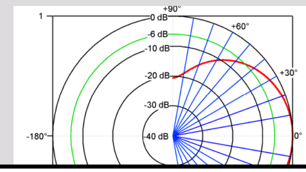


Frontal Polar Pattern of Two Separated Point Sources Versus Wavelength Spacing

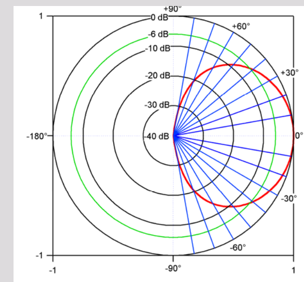
D/λ = 0.1,
Beamwidth = 180º



D/λ = 0.47,
Beamwidth = 90º

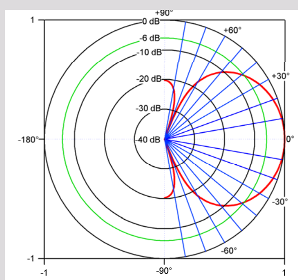


D/λ = 0.5,
Beamwidth = 83.6º

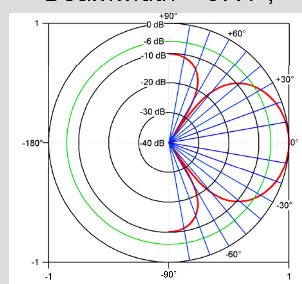


Note narrowing of pattern and increasing side-lobe levels at higher frequencies.

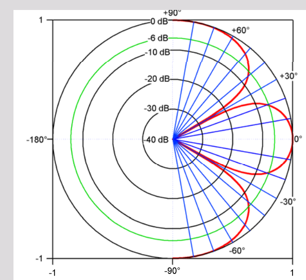
D/λ = 0.53,
Beamwidth = 77.5º



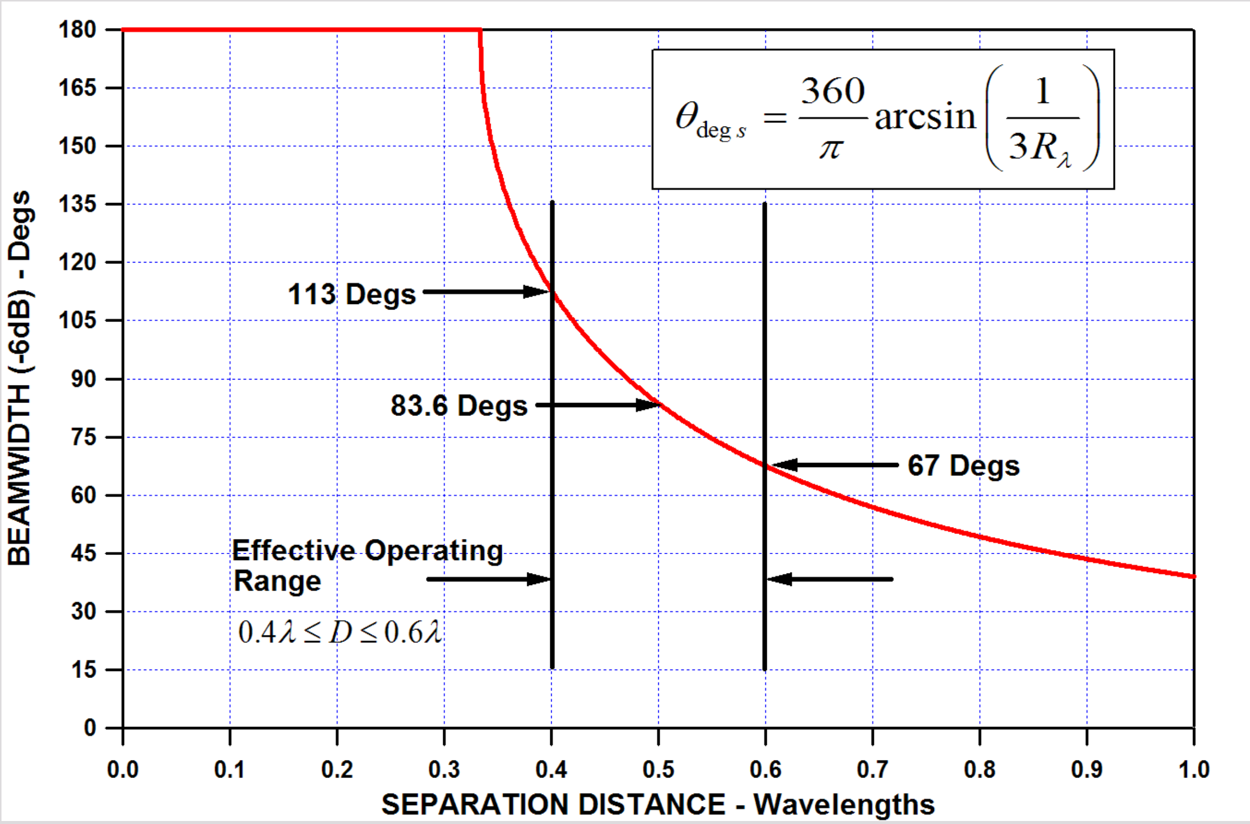
D/λ = 0.6,
Beamwidth = 67.1º,



D/λ = 1,
Beamwidth = 38.7º

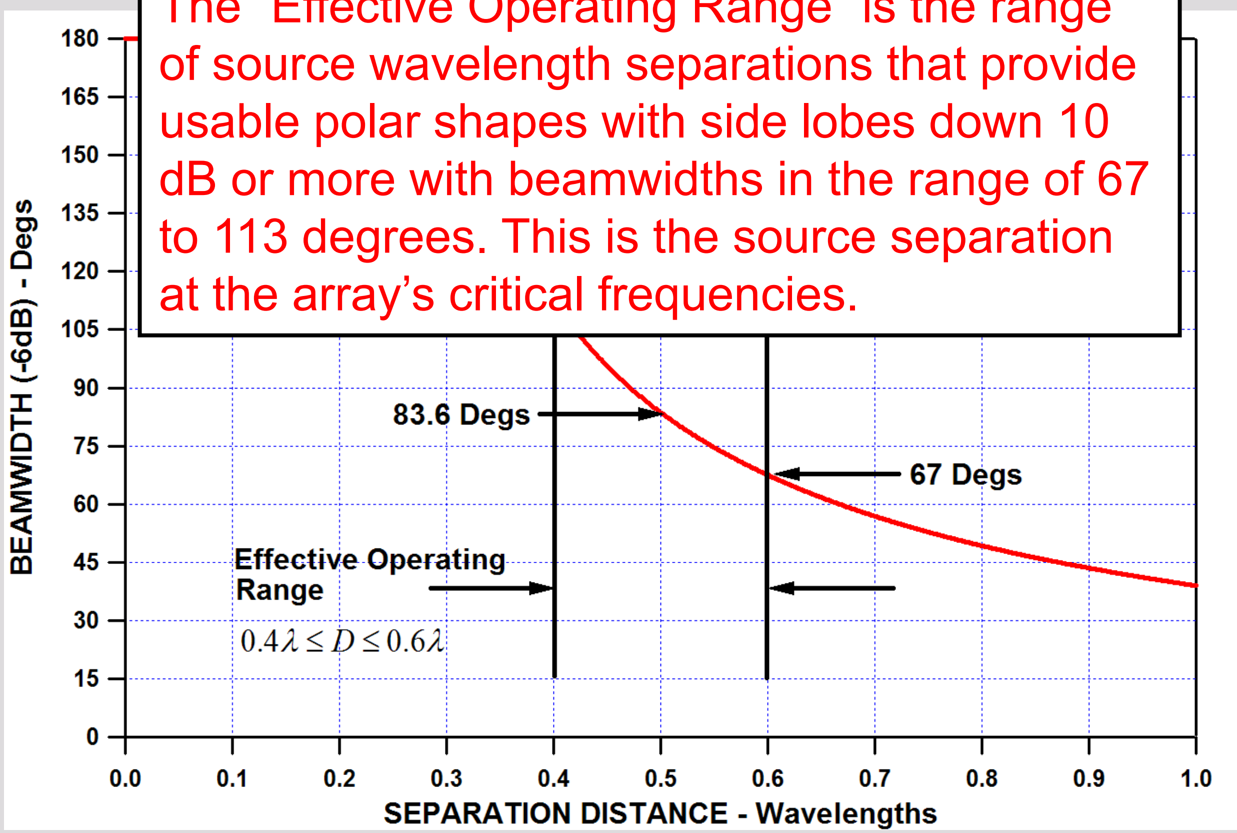


Vertical Beamwidth (-6 dB) vs. Separation Distance

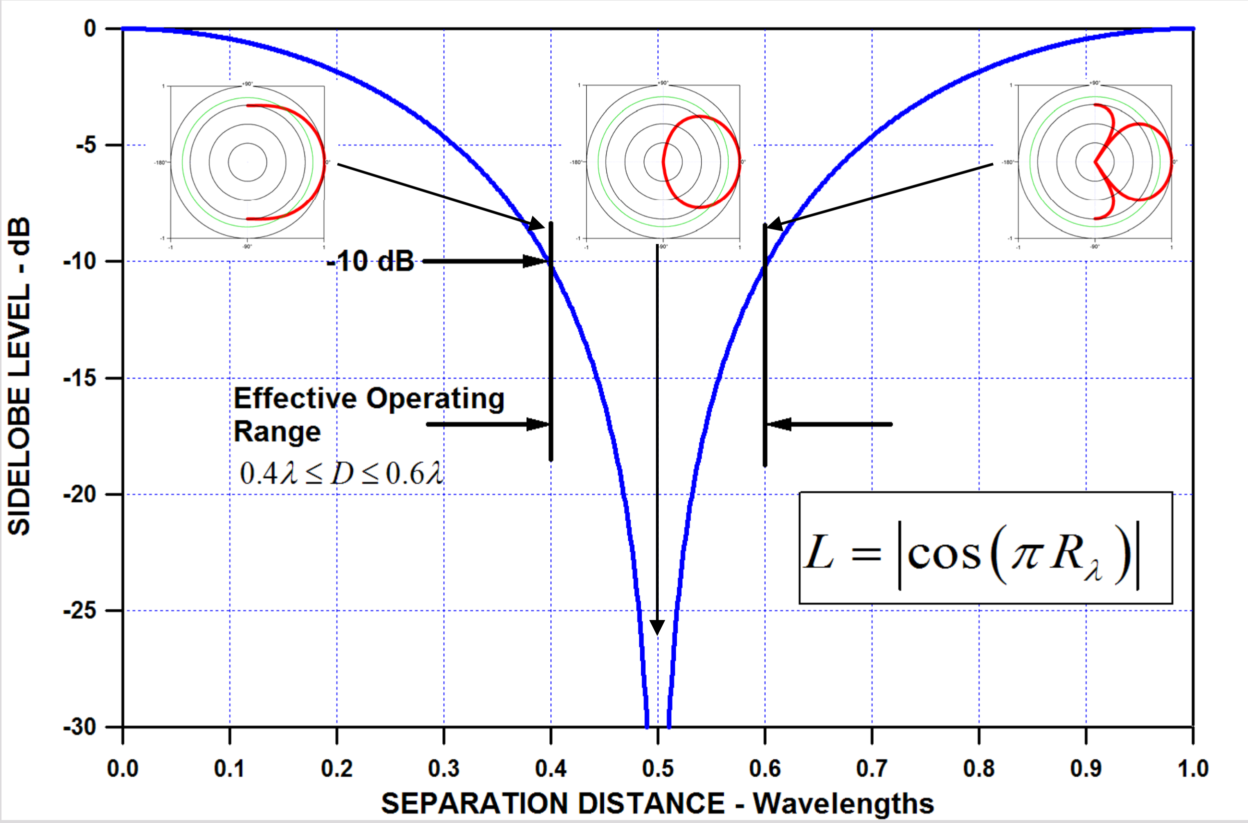


Vertical Beamwidth (-6 dB) vs. Separation Distance

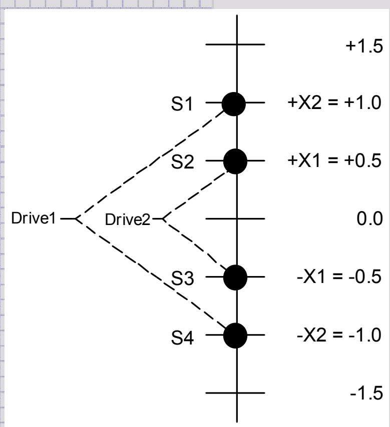
The “Effective Operating Range” is the range of source wavelength separations that provide usable polar shapes with side lobes down 10 dB or more with beamwidths in the range of 67 to 113 degrees. This is the source separation at the array’s critical frequencies.



Side Lobe Level (at ±90º) vs. Separation Distance



Linear Combination of the Patterns of Two Pairs of Separated Point Sources

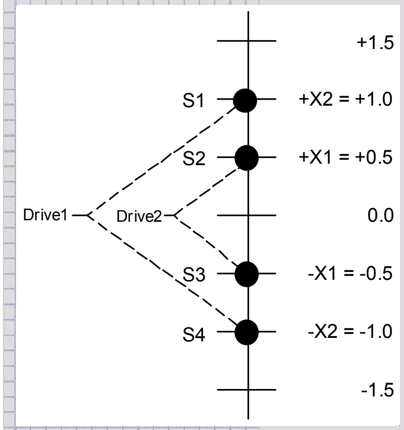


- Part 1 shows that a linear combination of the acoustic outputs of adjacent pairs of drivers can maintain essentially flat off-axis frequency response over a significant range of off-axis vertical angles.
- Part 2 will show that this linear combination of outputs can also maintain beamwidth and vertical polar shape in the same range of frequencies.

Polar Pattern Summing for Two Pairs of Separated Point Sources

- The following series of graphs illustrate that it is possible to approximate a desired polar pattern by linearly summing the patterns of two pairs of sources over a range of frequencies, although the patterns of the individual pairs of sources may be incorrect!

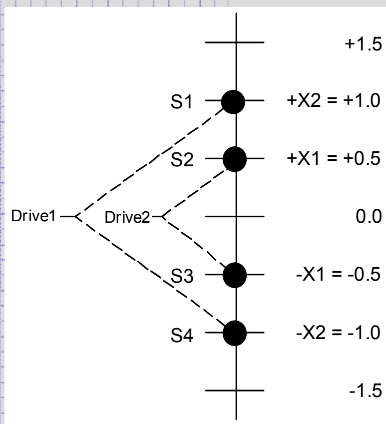
Constant Beamwidth Frequency and Summing Ratios for Two Pairs of Sources



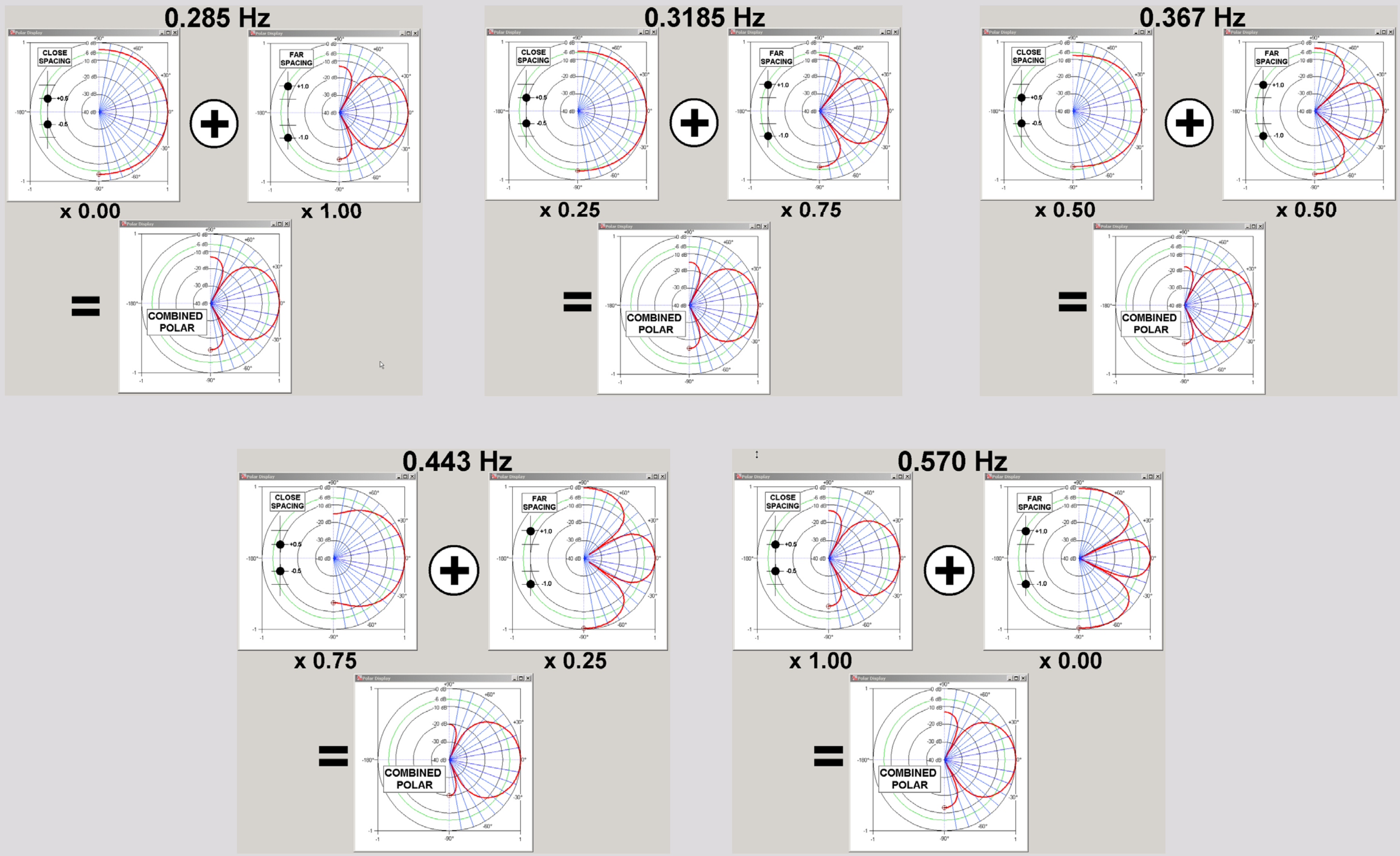
Frequency Identifier	Normalized Frequency	Drive1 (Outermost Sources S_1 and S_4)	Drive2 (Innermost Sources S_2 and S_3)
1) Lower critical frequency	0.285	0.00 (Off)	1.00 (Full on)
2) Intermediate frequency	0.3185	0.25	0.75
3) Intermediate frequency (crossover)	0.367	0.50	0.50
4) Intermediate frequency	0.443	0.75	0.25
5) Upper critical frequency	0.570	1.00 (Full on)	0.00 (Off)

harman international
harman consumer group
HARMAN/BECKER AUTOMOTIVE SYSTEMS

b)



Polar Pattern Summing Over a Range of Frequencies

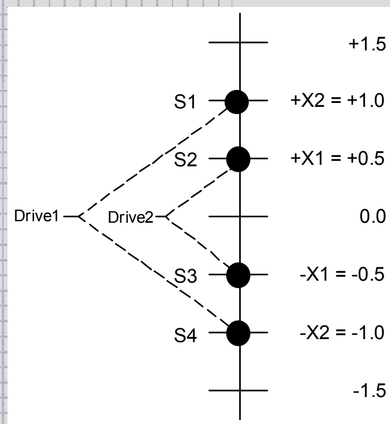


harman international

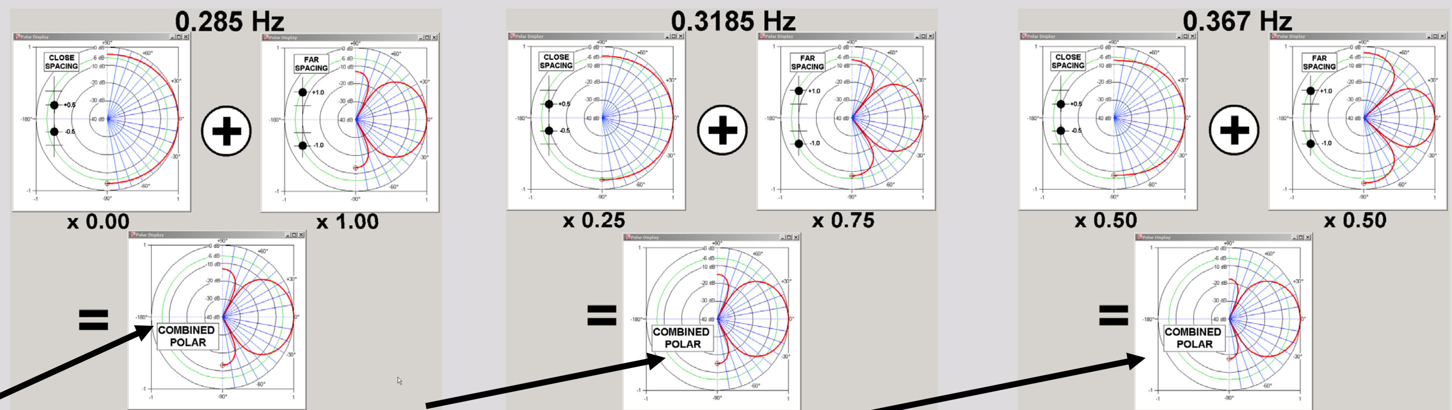
harman consumer group

HARMAN/BECKER AUTOMOTIVE SYSTEMS

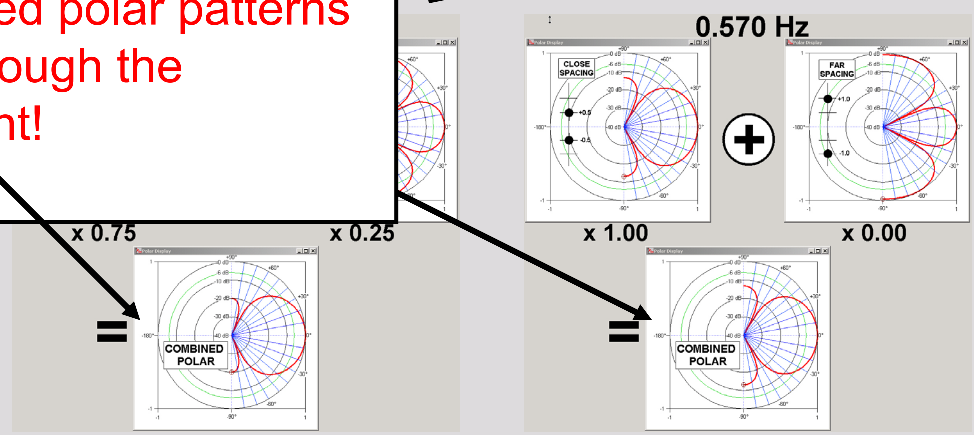
b)



Polar Pattern Summing Over a Range of Frequencies



Note that the resultant summed polar patterns are roughly the same even though the individual patterns are different!
This over an octave range!

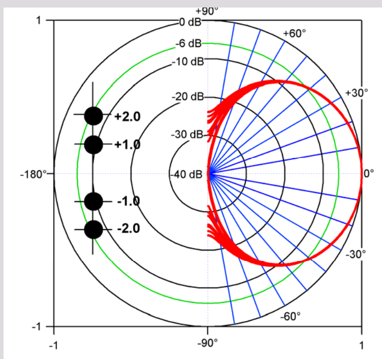


harman international
harman consumer group
HARMAN/BECKER AUTOMOTIVE SYSTEMS

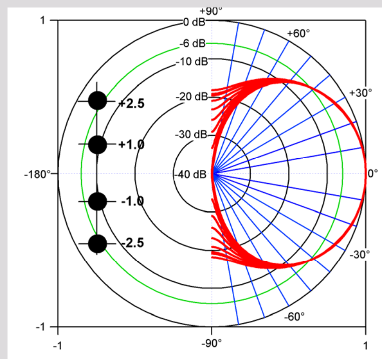
Polar Pattern Overlays for a Double Pair of Sources Separated by Different Spacing Ratios

for a Critical Design Wavelength of 0.5 λ

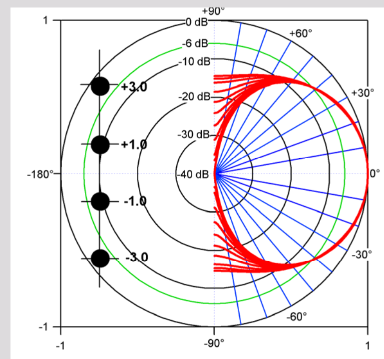
Ratio = 2:1



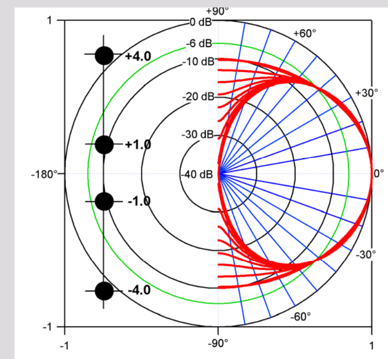
Ratio = 2.5:1



Ratio = 3:1



Ratio = 4:1

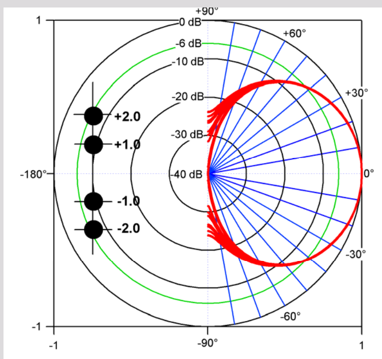


To generate each polar overlay, the frequency was varied in 10 steps between the two critical frequencies so as to maintain a constant beamwidth of 83.6º.

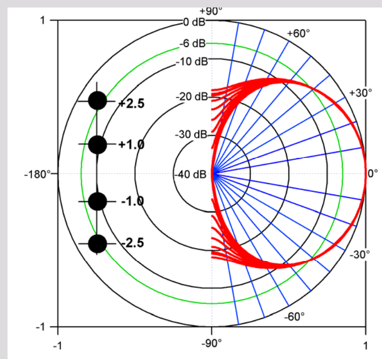
Polar Pattern Overlays for a Double Pair of Sources Separated by Different Spacing Ratios

for a Critical Design Wavelength of 0.5 λ

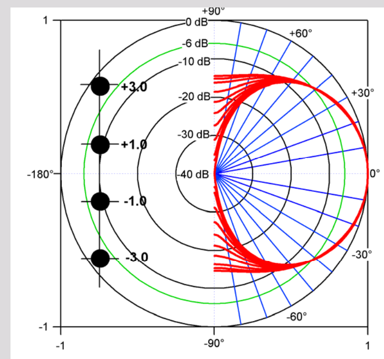
Ratio = 2:1



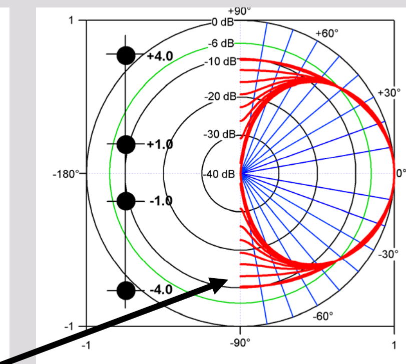
Ratio = 2.5:1



Ratio = 3:1



Ratio = 4:1

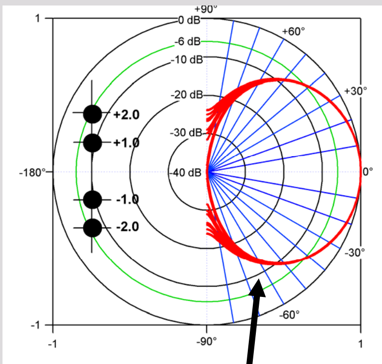


Note that as the spacing ratio increases, the polar uniformity at angles beyond the 6-dB-down angle decreases dramatically!

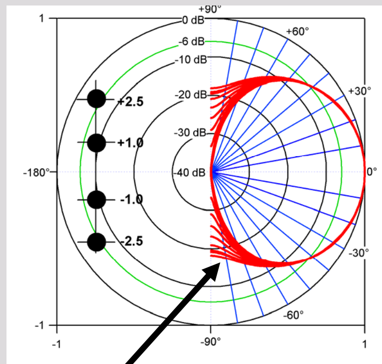
To gene … d in 10 steps
betwee … constant
beamw …

Polar Pattern Overlays for a Double Pair of Sources Separated by Different Spacing Ratios for a Critical Design Wavelength of 0.5 λ

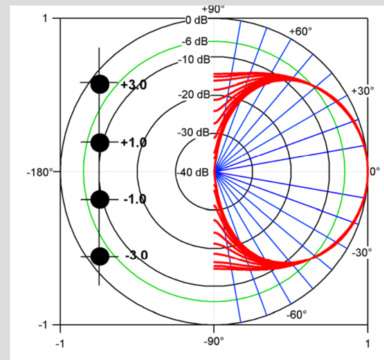
Ratio = 2:1



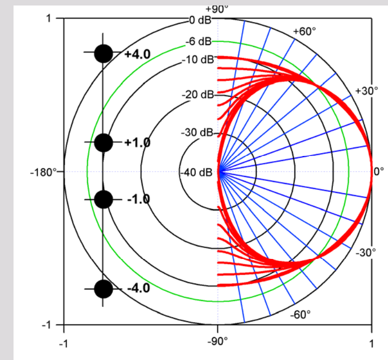
Ratio = 2.5:1



Ratio = 3:1



Ratio = 4:1



T… he frequency was varied in 10 steps
b… ies so as to maintain a constant
b…

Spacing ratios in the range of 2:1 to 2.5:1 provide good uniformity out to about 12 to 15 dB down from on axis.

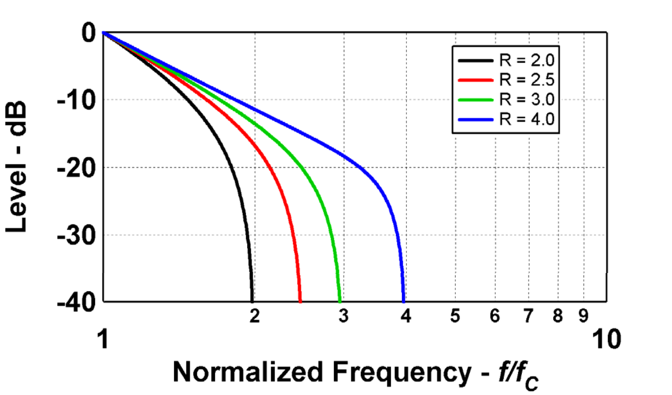
Calculation of Crossover Frequency Responses

The equations are frequency normalized to span only the range between the two critical frequencies (or spacing) of the source pairs.

Implicit in the derivation of these equations is that the beamwidth at the 6-dB-down points is maintained at all intermediate points between the critical frequencies!

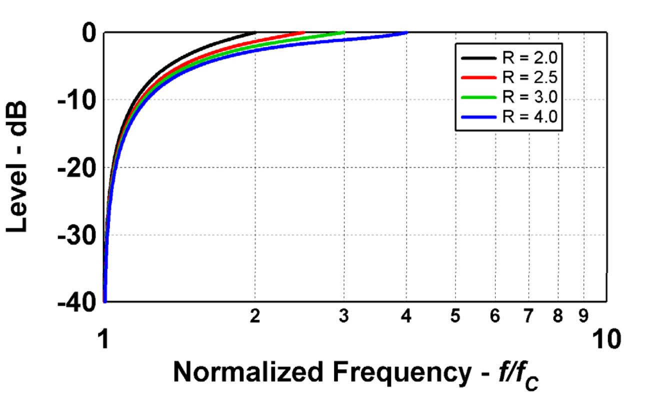
Low-pass Crossover Responses for Several Critical Frequency Ratios

$$H_{LP}(f_N, R) = \begin{cases} \frac{1}{2}\left|\dfrac{2\cos\left(\frac{\pi f_N}{3R}\right)-1}{\cos\left(\frac{\pi f_N}{3}\right)-\cos\left(\frac{\pi f_N}{3R}\right)}\right| & \text{for } 1 \le f_N \le R \\ 0 & \text{otherwise} \end{cases}$$



High-pass Crossover Responses for the Same Critical Frequency Ratios

$$H_{HP} = 1 - H_{LP}$$



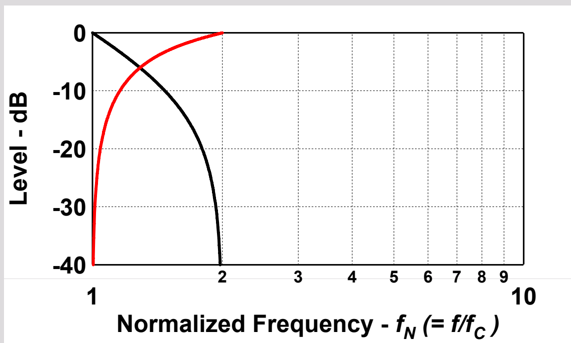
harman international

harman consumer group

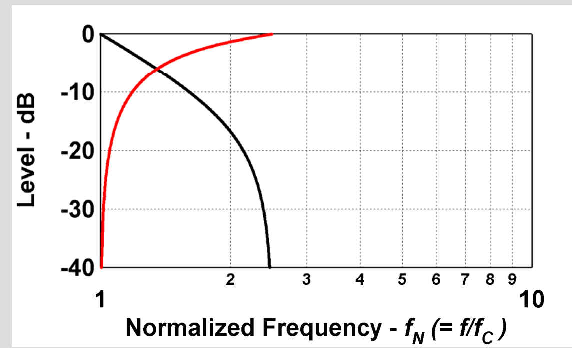
HARMAN/BECKER AUTOMOTIVE SYSTEMS

Look at the Individual Crossover Responses for each Critical Frequency Ratio or Spacing Ratio

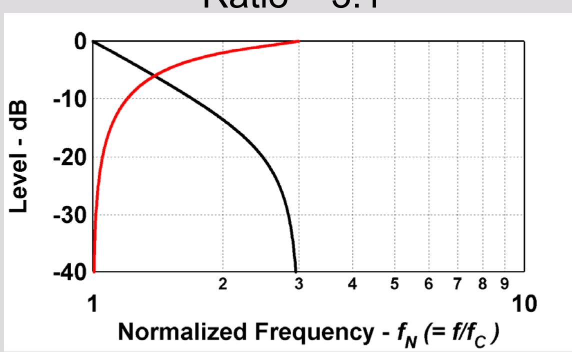
Ratio = 2:1



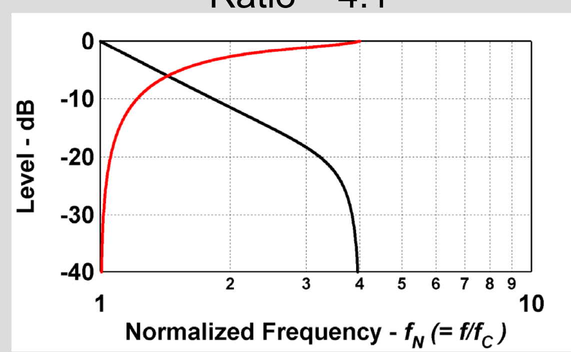
Ratio = 2.5:1



Ratio = 3:1



Ratio = 4:1



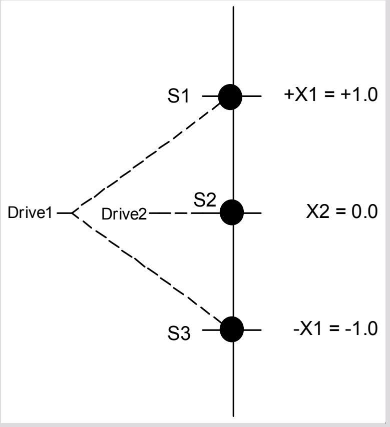
harman international

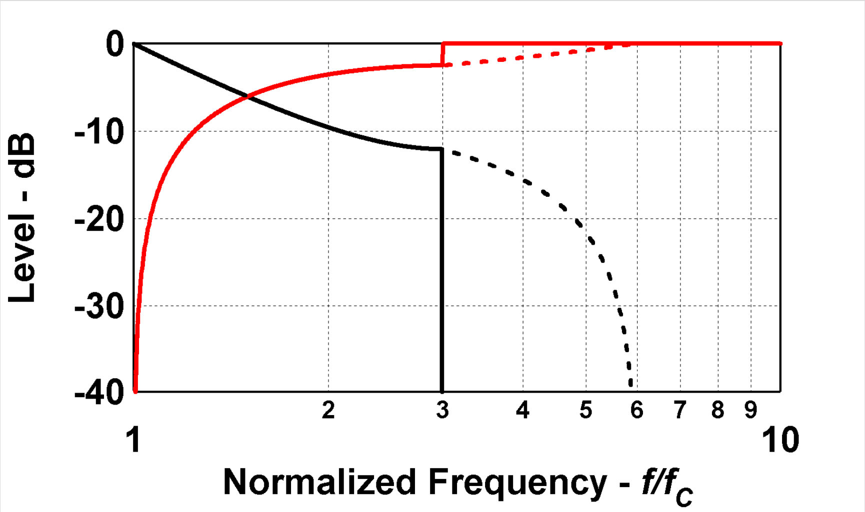
harman consumer group

HARMAN/BECKER AUTOMOTIVE SYSTEMS

What Do You Do With the Single Central Tweeter at High Frequencies?

$$H_{LP}(f_N) = \begin{cases} \frac{1}{2}\left(\frac{1}{1-\cos(\frac{\pi f_N}{3})}\right) & \text{for } 1 \le f_N \le 3 \\ 0 & \text{otherwise} \end{cases}$$

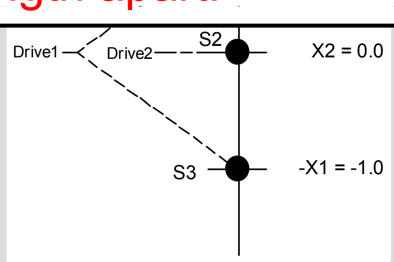


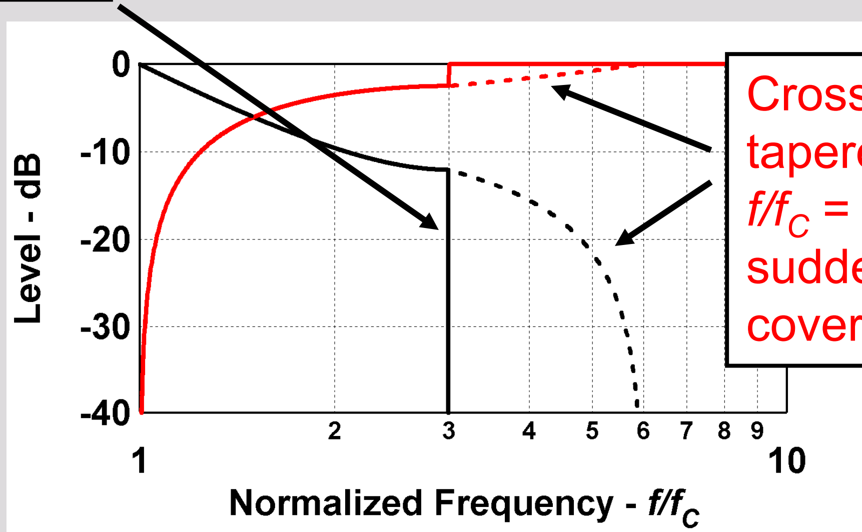


What Do You Do With the Single Central Tweeter at High Frequencies?

Can only maintain constant beamwidth over a three-to-one frequency range above the point where the outside sources are about one-half wavelength apart!

$$f_N) = \begin{cases} \frac{1}{2}\left(\frac{1}{1-\cos(\frac{\pi f_N}{3})}\right) & \text{for } 1 \le f_N \le 3 \\ 0 & \text{otherwise} \end{cases}$$



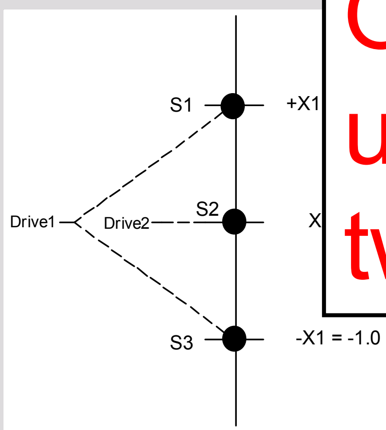


Crossover can be tapered above f/f_C = 3 to prevent sudden increase in coverage.

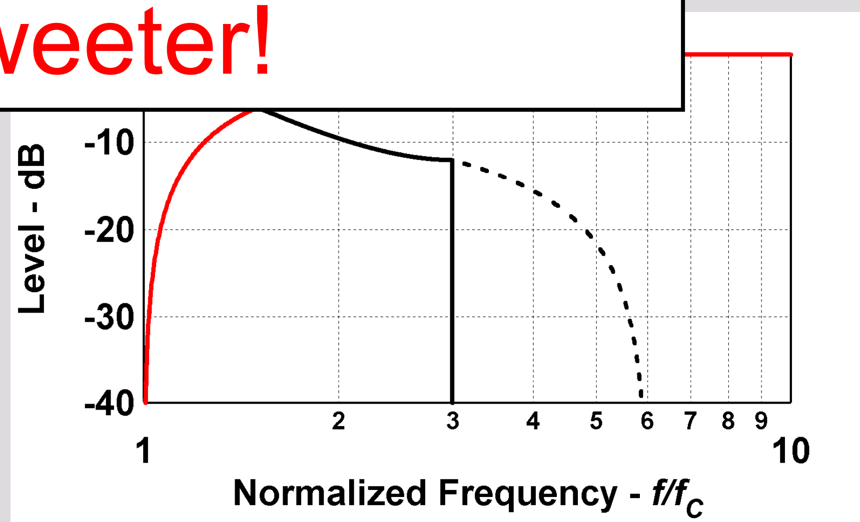
What Do You Do With the Single Central Tweeter at High Frequencies?

$1 \quad 1 \quad \le f_N \le 3$

wise



Or……..You can use a directional tweeter!



Five-Way Array Design Example

- Desired System Specifications:
  - Vertical beamwidth of 75º with side lobes down at least 17 dB.
  - Constant-beamwidth operating range of 100 Hz on up.
  - Height = 2 m (6.7 ft, 80 in) approximately.
  - Use two 15” sub woofers, two 8” woofers, two 4” lower midranges, two 2” upper midranges, and a single 1” dome tweeter.

System Parameters

Driver	Location (Inches)	Pair Spacing (Inches)	Critical Freq. (Hz)	Step Ratio	Crossover Frequency (Hz)
Two - 15" Sub Woofers	±31.25	62.5	119	2.5	160
Two - 8" Woofers	±12.50	25.0	297	2.78	408
Two - 4" Lower Midranges	±4.50	9.0	825	3.00	1,150
Two - 2" Upper Midranges	±1.50	3.0	2,475	-	3,372
One - 1" Dome Tweeter	0.00	-	-	-	-

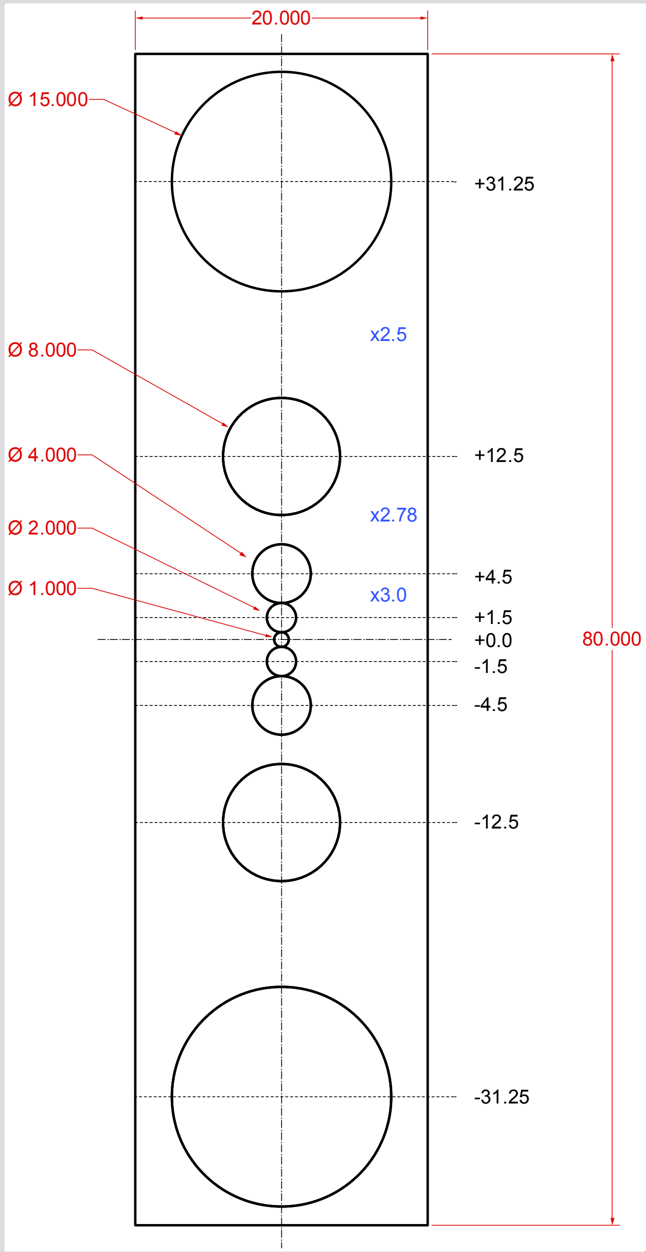
harman international

harman consumer group

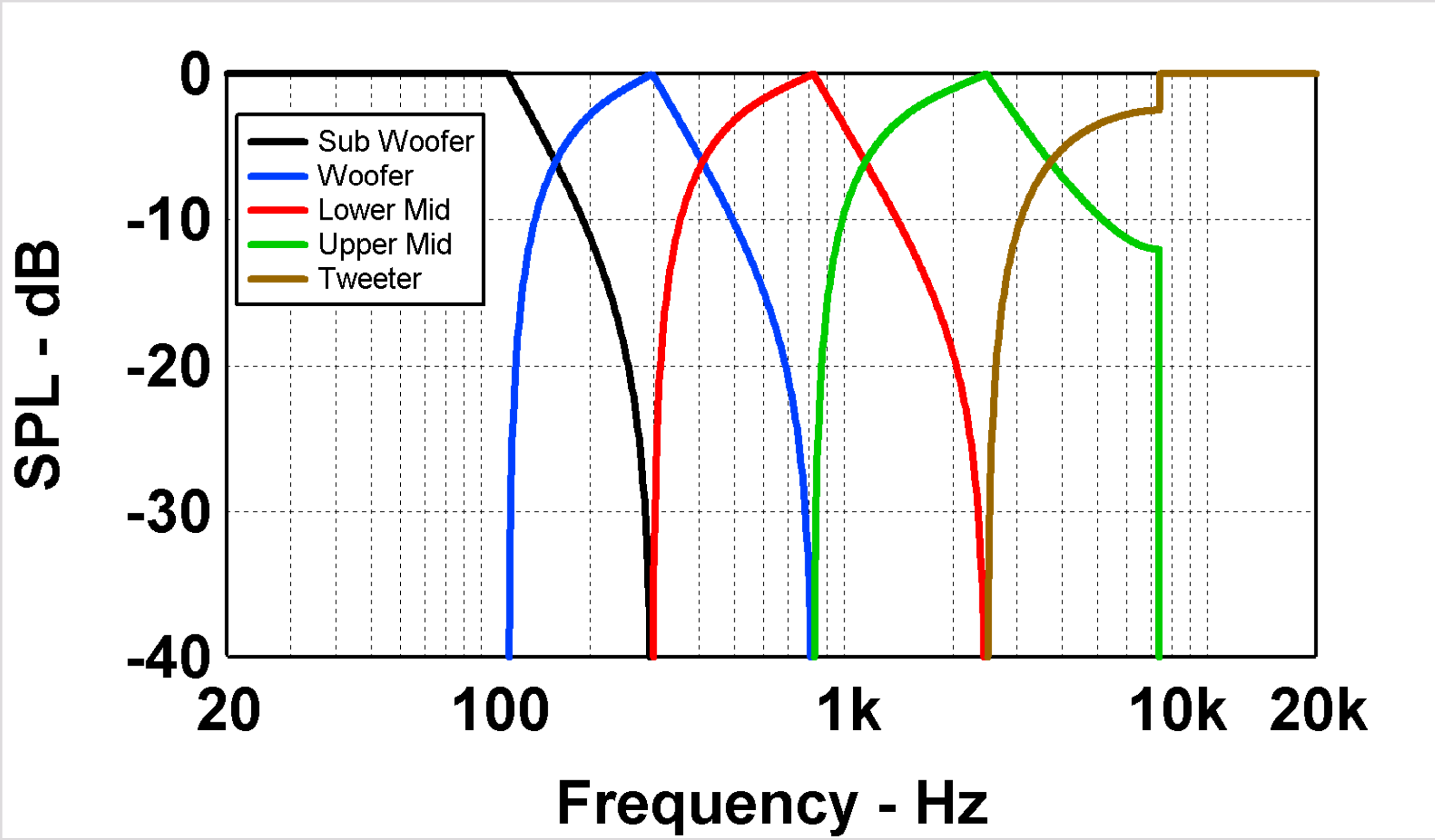
HARMAN/BECKER AUTOMOTIVE SYSTEMS

Front Panel Design

The chosen 75º vertical beamwidth and the lobe requirement dictates a critical driver spacing of about 0.55 wavelength.

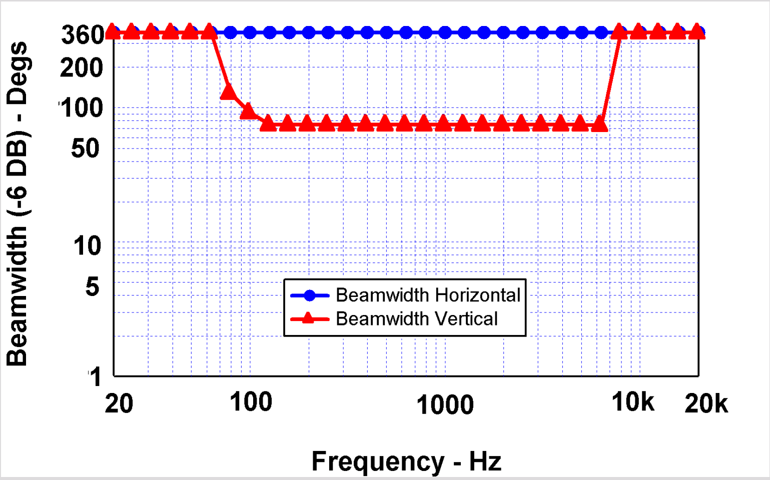


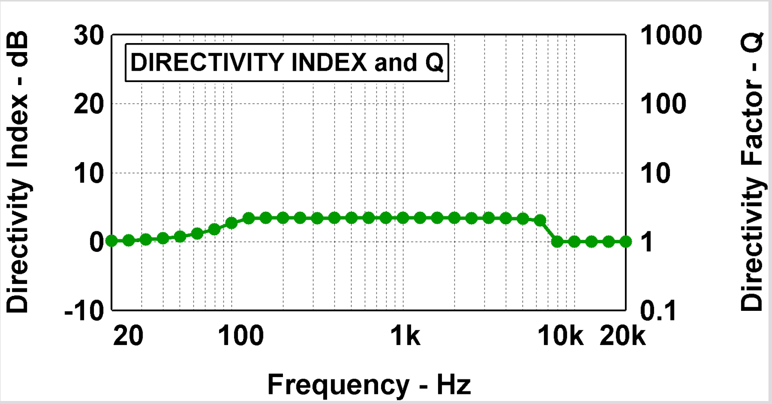
Crossover Frequency Responses



Beamwidth and Directivity

(Note: Directivity is defined in a half space where an omni-directional source has directivity of 1 or a directivity index of 0 dB.)





harman international

harman consumer group

HARMAN/BECKER AUTOMOTIVE SYSTEMS

Summary

- In this paper we described a new linear-phase DSP technique for crossing over multi-way loudspeakers utilizing pair-wise symmetric driver configurations with a central tweeter in a vertical array.
- The technique is based on combining the acoustic outputs of pairs of drivers to yield a flat frequency response at an arbitrary specified off-axis angle.
- In contrast to prior crossover techniques such as Linkwitz-Riley, constant-voltage, linear-phase Remez, etc., the new technique actually maintains flat off-axis frequency response throughout most of the operating range of the speaker except at high frequencies where the single central tweeter operates on its own.

Summary Cont.

- The technique produces a crossover filter frequency response with a very distinctive pointed-top shape.
- On either side of the point, called a critical frequency, the response rolls off rapidly and essentially shuts off at frequencies above and below the critical frequencies of the adjacent drivers.
- At a critical frequency, only one pair of drivers are energized.
- At frequencies between the critical frequencies, only two pairs of speakers are operating.

Summary Cont.

- In part 2 we restricted the level of the forced-to-be-flat off-axis angle to -6 dB thus making it equal to the level of the polar beamwidth specification, the angle between the 6-dB-down points from on axis.
- The spacing of each pair of drivers at their critical frequencies should be in the range of 0.4 to 0.6 wavelength to yield well-behaved polar shapes with beamwidths in the range of 67º to 113º.
- The spacing ratios between successive pairs of drivers should preferably be in the range of 2:1 to 2.5:1, but can extend out to 4:1, but at the expense of polar uniformity at angles beyond the 6-dB-down points.

Thank you!