



Technical Notes Volume 1, Number 29

JBL Precision Directivity™ PD700 Series Co-Axial Mid/High Speaker Systems

Background:

In very large fixed installations, such as sports arenas, large houses of worship, or theatres, the requirements for wide bandwidth, dynamic sound reproduction have steadily increased over the past two decades.

Traditional solutions focused on arrays of “bins and horns”, but such solutions are often no longer in keeping with the increased aesthetic requirements of the venues themselves. Furthermore, wide-bandwidth, high-fidelity-sound-reproduction at higher SPL's is difficult to achieve with traditional solutions.

In the more recent past, a number of manufacturers have introduced packaged systems to address some of these requirements, but with only varying degrees of success.

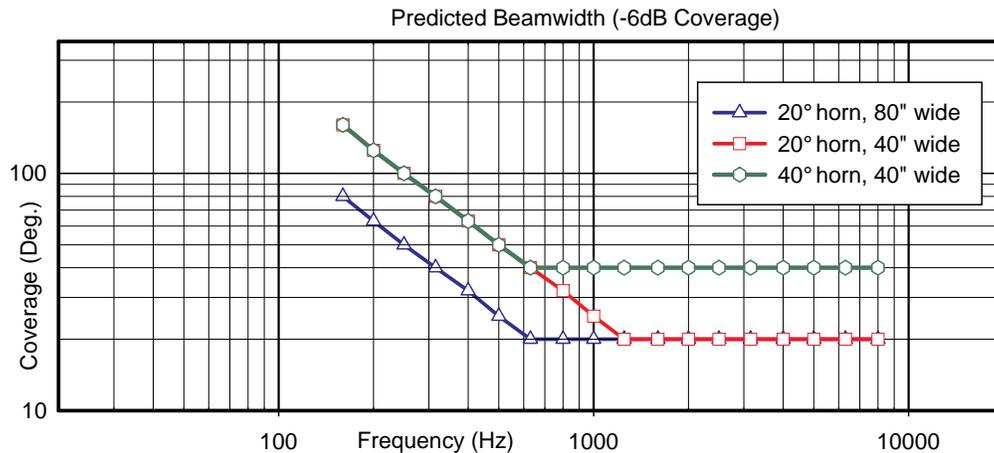
One of the limitations of many of these packaged systems is the inability of a single enclosure, aimed in the correct direction, to provide the required SPL in the audience area, due to the long distances between the loudspeakers and the audience. In a sports arena, a common specification for SPL is 105 dB continuous in the seating area, approximately 40 M (120 feet) from the loudspeaker.

There are a number of solutions which attempt to achieve these requirements but most are “work-arounds” based on existing technology, instead of true solutions.

One possibility, often employed, is to “overlap” the coverage of the loudspeakers. The downside of overlapping coverage patterns is the resulting destructive interference, which hampers the quality of reproduction, and only produces an increase in average SPL of approximately 3 dB over that of a single enclosure. In comparison, perfectly coherent summation between two sources through their entire coverage pattern would increase average SPL by 6 dB.

Another way to increase the SPL generated by an enclosure is to decrease the coverage angle of the enclosure in order to increase the directivity or “Q”. But to maintain pattern control as the coverage angle is decreased, the size of the horn must increase in direct proportion. For example, a 40° horn that is 1 m (40 in.) tall, would need to be 2 m (80 in.) tall to maintain it's nominal coverage angle at 625 Hz, if the targeted coverage were decreased to 20°. Clearly the size of such a horn would be impractical for most applications.

Figure 1: Predicated beamwidth of three horn designs, comparing mouth size and design coverage angle.



As a compromise, if the coverage of a horn is made narrower but the size is kept the same, at lower frequencies the pattern control of the narrower coverage horn remains identical to the wider coverage angle horn, as is shown in figure 1. The example 40" horn that is nominally 20° coverage only provides full pattern control above 1250 Hz.

In some solutions, two or more high frequency horns are installed in the same enclosure, and the resulting destructive interference is accepted as a compromise, or simply isn't discussed. But once again only a 3 dB increase in average SPL results, instead of the 6 dB increase that is possible if the devices summed in a coherent fashion everywhere in the coverage pattern.

Introduction to the PD700 Co-axial Series:

After reviewing the existing physical limitations it was clear that a loudspeaker enclosure that is capable of maximum SPL 6 dB greater than current designs would require two high-sensitivity midrange-cone transducers, and two large-format compression drivers. The wavefronts of the devices need to combine in a fully coherent manner everywhere within the coverage of each enclosure to meet the goal of a 6dB increase in maximum SPL.

Additionally, a co-axial mid-high horn arrangement with a square face was chosen so the side walls of the midrange horns could be brought close together for improved midrange arrayability, and also

to allow the enclosures to be rotated in an array. To allow the face of an array to be a virtually gapless spherical section, the enclosures were made trapezoidal in both planes.

The systems developed to meet these requirements are the JBL Precision Directivity PD700 series. Models available include the PD743 and PD764 (40° x 30° and 60° x 40° coverage). PD700 models are designed to crossover to the low frequency system at 225 Hz. For example, a low-frequency system consisting of PD162 Forward Steered Array modules is an ideal solution for larger venues.

Models in the PD700 Series of mid-high enclosures offer the following features:

- Square faced enclosures which are trapezoidal in both planes allowing systems to be rotated.
- Co-axial mounting of the high frequency horn flush with the face of the midrange horn.
- Dual large-format 75 mm (3 in) diaphragm Neodymium 2430H compression drivers.
- Unique 53 mm (2.1 in) aperture dual driver high frequency throat section for interference free summation.
- Constant directivity horns for predictable arrayability.
- Dual 2250J 200 mm (8 in) diameter Neodymium Differential Drive® (NDD™) midrange drivers, for 700W total power handling and maximized midrange clarity.
- Midrange acoustic damper to eliminate midrange throat reflections.
- Optimized recommended processor settings to provide matched crossover polar response.

Coaxial Mid-High Systems – An Overview on Performance:

Although co-axial systems can provide distinct performance advantages, they are often plagued by design difficulties and flaws that negate the performance gains. We'll begin by examining some of the typical performance benefits of a co-axial design. Then we'll examine the performance limitations which may occur in a co-axial design. Finally we'll describe how the PD700 series Mid-High systems address the limitations, while realizing performance benefits available.

Co-axial Benefits:

An important benefit of a co-axial mid-high system is that, through the crossover region, the system behaves symmetrically about the horizontal and vertical planes. As a result, off-axis interference between the mid and high frequency sections can be virtually eliminated by carefully controlling the geometry and location of the components, and by applying optimized signal processing to the pass bands. Such processing is described in a later section of this paper.

The second benefit is the compact size of a co-axial design. The frontal area of the system can be greatly reduced in a co-axial configuration. As an example, the PD743 is 990 x 990 mm (39 x 39 in.) in height and width. If the high frequency horn were above, or to the side, of the midrange horn then the resulting system, with equivalent pattern control, would be 1350 x 990 mm (53 x 39 in.). In other terms: the frontal area of the enclosure would be 36% larger. The smaller frontal area can be a substantial benefit in meeting architectural goals of compact array size.

An additional benefit of a co-axial design appears when the enclosures are used in an array. The co-axial enclosure allows the midrange horns to be placed sidewall-to-sidewall, both horizontally and vertically, allowing the midrange wavefront to radiate from each enclosure with virtually no gaps. As a result, the coupling of the midrange horns is far more predictable, the system is easier to tune, and the final coverage is more uniform in the audience areas.

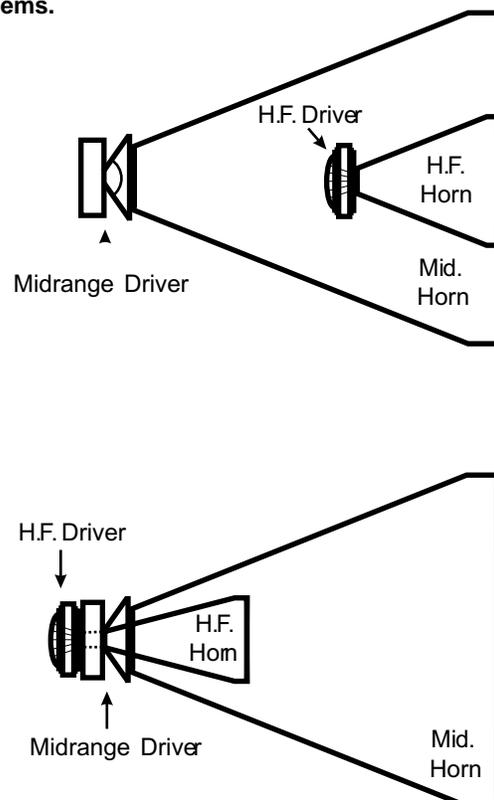
Finally, if the face of the co-axial enclosure is square, and the enclosure is trapezoidal in both planes, then the enclosure will ideally have no preferential axis, and will be equally effective in both orientations. For example a 40°x30° system would function equally well as 30°x40° system. To the consultant this allows much more freedom in the design of a cluster.

Addressing Co-axial Design Challenges:

Co-axial systems have not been universally accepted, even though there are clear benefits. A major reason for this lies in the difficulties in designing a co-axial system, which are often not adequately addressed and result in design problems that negate the potential gains. We'll now discuss these problems, and how they were addressed in the PD700 series.

In a co-axial mid-high horn loaded system the compression driver may be mounted behind the midrange driver, and then fire through the pole piece of the driver. The alternative arrangement is to place the high frequency driver in front of the midrange cone, or phase plug exit. An example of each configuration is shown in Figure 2.

Figure 2: Two typical designs of co-axial mid-high systems.



The problems that result from having the high frequency driver fire through the midrange driver include high 2nd harmonic distortion caused by the low expansion rate in the narrow long throat section. (See Reference 1 for a discussion of compression driver throat distortion). Often, to avoid excessively masking the mouth of the midrange horn, this configuration requires that the high frequency horn terminate before the mouth of the midrange horn, which can result in HF energy diffracting and reflecting into the midrange horn. For these reasons this configuration was eliminated as a possibility for the PD700 series.

The second configuration places the high frequency driver in front of the midrange driver, or in front of the midrange horn throat. This configuration allows more flexibility in the design of the high frequency horn and potentially offers better performance.

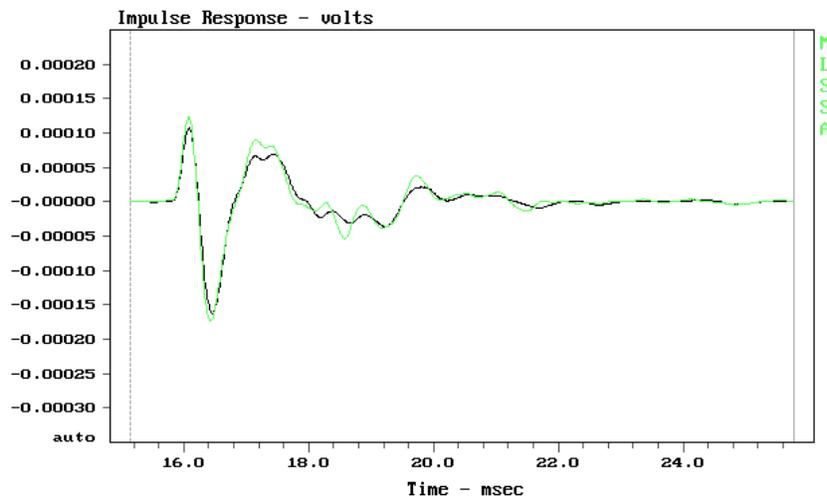
Eliminating Midrange Reflections and Resonances:

Two design challenges result when the compression driver and horn are located in front of the midrange transducer, in the mouth of the midrange horn. The first problem is reflections off the rear of the compression drivers, back down the throat of the midrange horn, and the aberration in frequency response, and polar response that may result. The second problem is the high-frequency horn acts as obstruction to the proper expansion of the midrange horn and may generate resonances.

To address the first problem, the PD 700 series incorporates two features. First, the high frequency transducers are placed very close to the midrange drivers, this eliminates reflections at the lower frequencies. To eliminate reflections at higher frequencies, an “acoustic throat damper” was designed. The damper is specified to be moderately acoustically absorptive above 700 Hz, but not to be absorptive at lower frequencies. The throat dampers are constructed with an inside and outside shell of flame-retardant-treated and acoustically transparent woven fabric. The benefit is much smoother polar response, and a visibly and audibly cleaner impulse response, as shown in Figure 3. The acceptable compromise is a net reduction in output of 1 dB from 1 to 2 kHz.

To address the problem of the high horn interfering with the expansion of the mid horn, unique high frequency horns were designed that have both an interior surface, and a molded outer surface as well. JBL’s extensive experience in composite construction was applied. The outside surface is molded to provide the correct area expansion of the midrange horn for proper acoustic loading. The space between the inside and outside shell is filled with urethane foam which provides structural rigidity and acoustic damping. Typical co-axial designs in the past have placed a “thin-wall” high-frequency horn in the mouth of the midrange horn, which results in frequency response and pattern control aberrations.

Figure 3: Midrange impulse response with and without acoustic throat damper. Solid curve shows response with damper, lighter curve shows response without damper.



Understanding Co-axial “Shadowing”:

Another design issue in a coaxial system is “shadowing”. If the percentage of the area of the midrange horn blocked by the high frequency horn is too large, then shadowing may occur. The effect causes the midrange horn to behave as two distinct “cells”, or signal sources. When this occurs, the midrange off-axis response has nulls within the nominal coverage angle. To solve this problem the size of the high frequency horn must be minimized, but must remain large enough to maintain pattern control at the crossover. A delicate design balance must be achieved.

Figure 4a is shown to visualize the problem of the midrange horn mouth being divided into separate acoustical radiating areas. We see three distinct areas indicated. These are defined by the top and bottom edges of the high frequency horn. Two large areas labeled ① are formed above and below the high frequency horn, and two smaller areas ② and ③ are shown on either side of the high frequency horn.

Figure 4a: Midrange horn shadowing – the radiating area of the midrange horn is visually divided into three zones 1, 2, and 3 for further analysis.

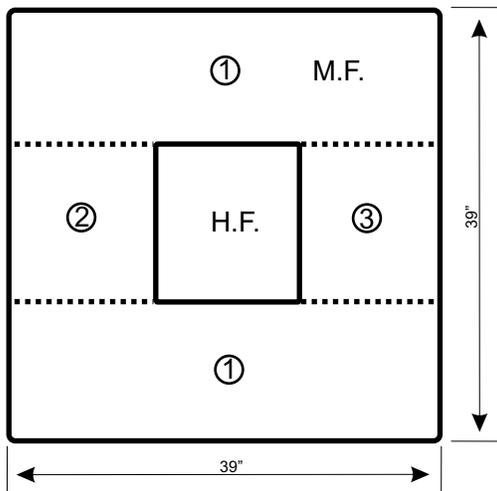
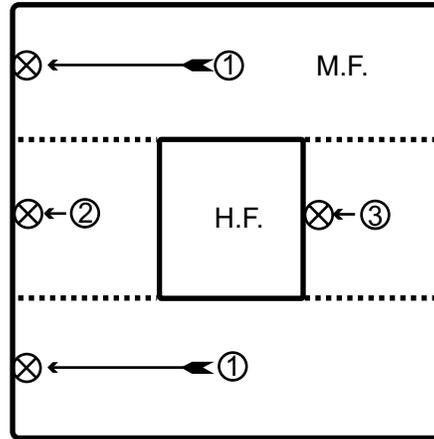


Figure 4b shows as the listening or measurement location is moved to the left, as indicated by the arrow, the vector that sound must travel through — indicated by the ⊗, shifts to the sidewall of the horn. At this angle of observation, acoustic energy originating from areas ① and ② is in the same vertical plane, but energy arriving from area ③ is offset in time. Figure 4b is a top view that shows

Front View:



Top View:

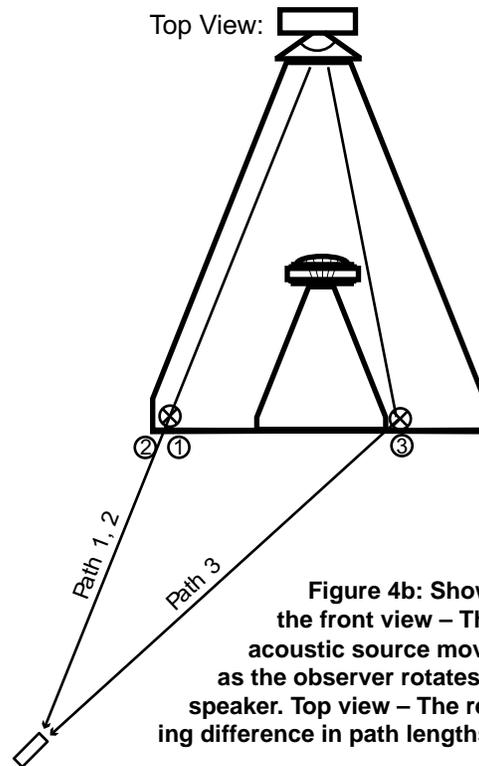


Figure 4b: Shown in the front view – The acoustic source moves left as the observer rotates the speaker. Top view – The resulting difference in path lengths.

this more clearly. The difference in time-of-flight for the delayed energy is apparent. If the area “shadowed” is too large, this difference in arrival time causes narrowing of the beamwidth, and visible lobing in the polar. Similarly the same effect may occur in the vertical plane.

Empirically, the height and width of the high frequency horn should be roughly no more than 0.3 to 0.4 of the height and width of the midrange horn, which keeps the area masked (area ③ on figure 4a) to between 13% to 19% of the total radiating area of the midrange horn.

Assuming the intensity of the sound field is uniform across the face of the radiating area of the mid-range horn, and assuming the worst case situation where the energy radiated from the “shadowed” zone is shifted 180° out-of-phase compared to the primary arrival of energy at some frequencies, the following results are calculated. For 13% masked area, a worst case, 2 dB maximum variation in response may occur. For 19% masked area this variation may be as much as 4 dB.

If the high frequency horn is not square, then the percentage masked is different in each plane — In the case of the PD743 the ratio of high/mid mouth height is 0.33 vertically, and 0.28 horizontally. Based on this analysis response variations should be no more than 2 dB. Polar plots and beamwidth plots show the resulting freedom from any masking problems in the PD700 series.

Geometry of the Dual Midrange & Dual HF Coaxial System:

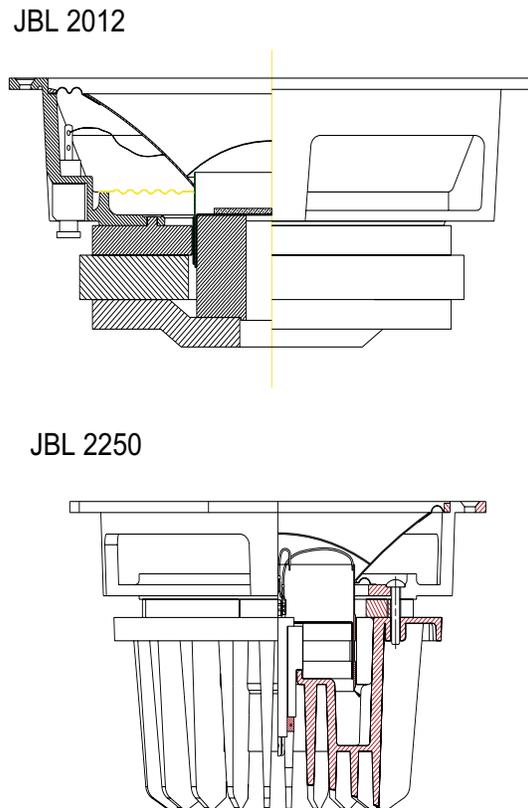
To achieve the goal of 6 dB greater output dual midrange drivers are required, but the output of the two drivers needs to combine coherently to realize a 6dB increase in maximum SPL. The midrange transducers chosen were the 200 mm (8 in.) diameter 2250J. This recent addition to JBL’s transducer family features JBL’s patented Neodymium Differential Drive® (NDD) technology, and provides 350 watt power handling, per transducer, with half the power compression of a traditional design.

Why was a 200 mm (8 in.) transducer chosen instead of a 250 mm (10 in.) transducer? The answer is three fold. The first reason is due to the smaller cone diameter of an 8” compared to a 10”. This allows the useful bandwidth of the driver to extend to a higher frequency. The second reason is the compact size NDD transducers can be placed edge-to-edge – only 196mm (7 ¾ in.) apart. This minimizes off-axis interference in the dual driver system.

Finally, despite the diminutive size and light weight, the 2250 is actually an extremely high output transducer for horn loaded midrange systems. For this application the two parameters that dominate in determining sensitivity and usable bandwidth are “motor strength”, or $(B \cdot L)^2 / R_e$, and “moving mass”,

M_{ms} . Examining the industry standard JBL 2012, the 2250 has a higher $(B \cdot L)^2 / R_e$ of 58.2 W compared to 41.5 W for the 2012. The moving masses of the two transducers are equal at 25 grams. Considering the higher motor strength, and equivalent moving mass, we see the 2250 is actually a higher sensitivity transducer on a horn that provides a sufficient impedance load.

Figure 5: Two midrange transducers: A traditional 10” design, and the 8” JBL NDD™ design.



Aligning the midrange drivers edge-to-edge vertically allows the high frequency drivers to be located between the two midrange drivers, as shown in figure 6b. Arranging the drivers this way significantly reduces the percentage area of the midrange radiating surface that is masked by the high frequency drivers.

As is discussed in the following section, two 2430 75 mm (3 in.) diaphragm compression drivers are used in a horizontally arrayed configuration. The 2430 driver is only 108 mm (4 ¼ in.) in diameter, and is ideal because the small surface area greatly

reduces midrange reflections in the co-axial application. As was discussed previously, the midrange throat damper eliminates the remaining higher frequency reflections.

The two vertically arrayed 2250 midrange drivers also serve to shorten the depth of the midrange horn considerably and provide pattern control to a lower frequency compared to a single driver. Figure 7 demonstrates why using only a single midrange driver would cause the midrange horn to be 380 mm (15 in) or 33% deeper, and more importantly would disturb the optimized spacing between the midrange cones and the rear of the compression drivers.

Figures 6a, 6b, and 6c are three-view drawing that indicate the features of a PD743 enclosure as we've described.

Figure 6A: Front View

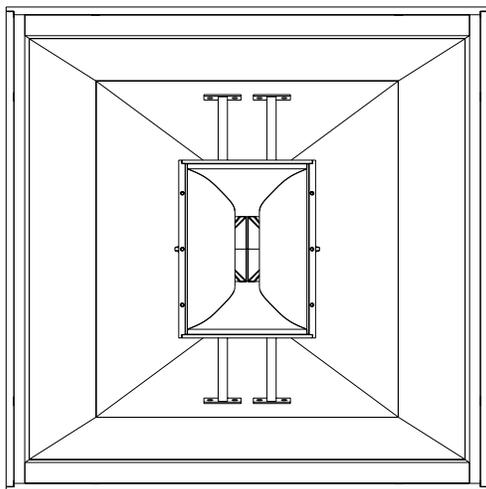


Figure 6B: Side Section View

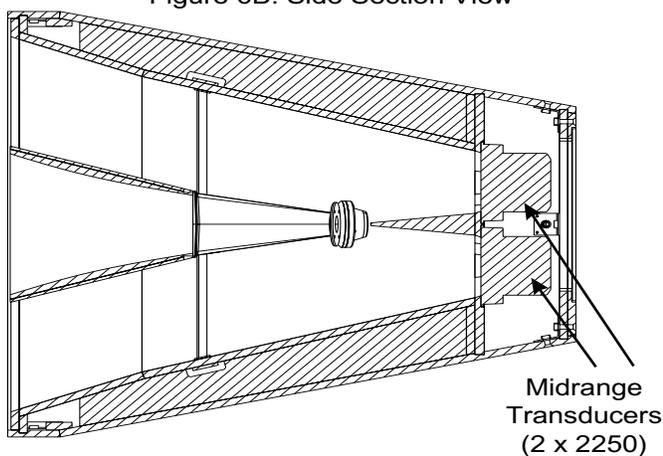


Figure 6C: Top Section View

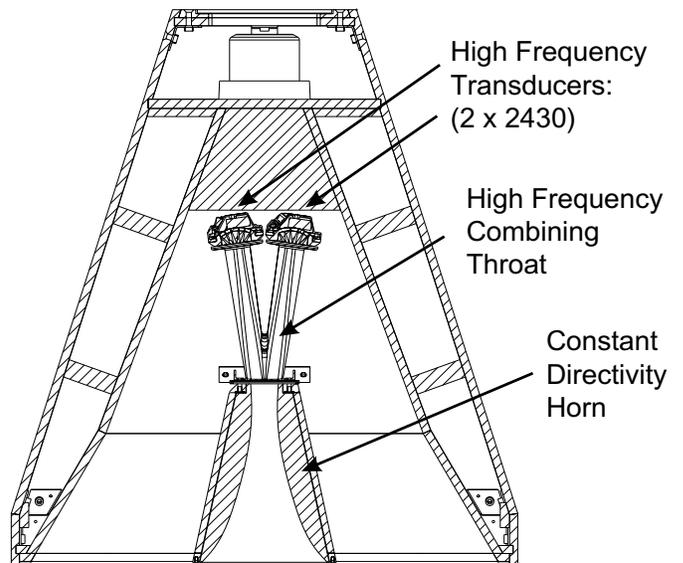
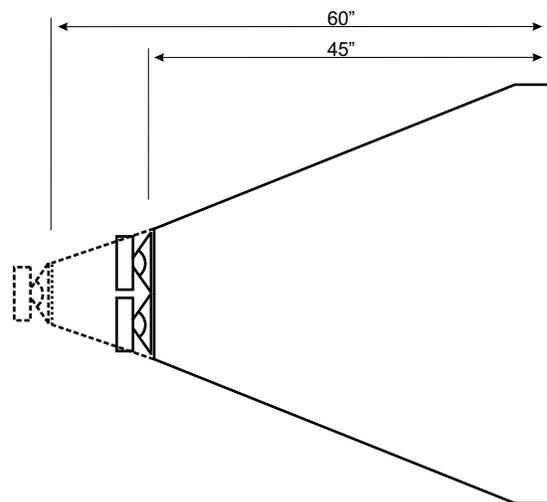


Figure 7: Benefit of a dual-driver midrange horn: Depth is reduced from 60" to 45".



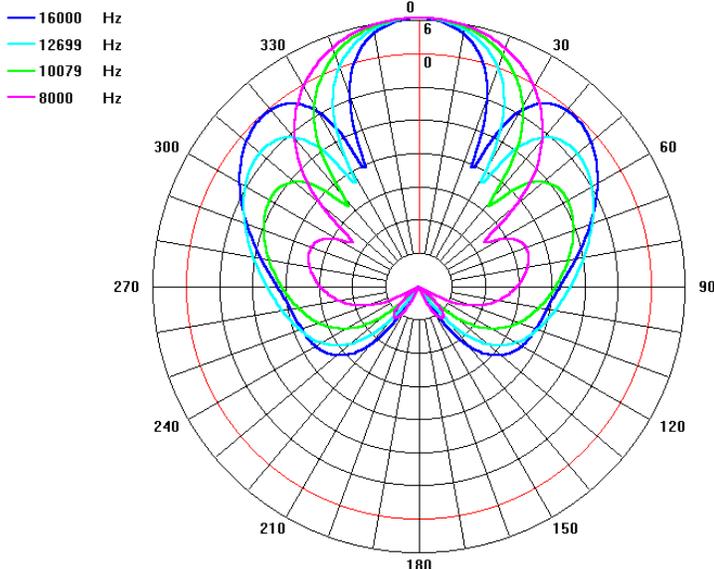
Performance of the Dual HF Driver System:

A key requirement in the PD700 series is to combine the output of two large format compression drivers without any destructive interference within the enclosure's nominal coverage to a frequency greater than 16 kHz. This interference free summation produces a 6 dB increase in maximum SPL compared to a single transducer.

The Challenge of Coherent Summation:

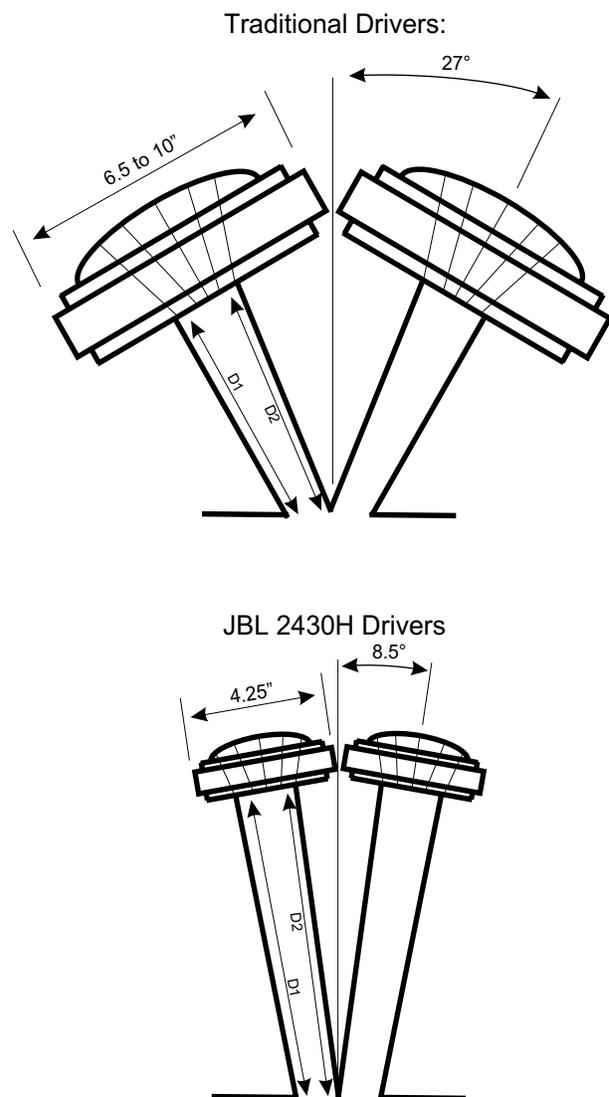
To achieve coherent summation the basic requirement is that two point sources must be coincident in space. Intuitively, we know this is not possible, so from a practical standpoint how close do the sources need to be to sum coherently to 16 kHz? A practical answer is that spacing of 25 mm (1 in.) or less between sources is sufficient. Figure 8 shows the interference pattern resulting in the polar response from two sources spaced 25 mm (1 in.) apart. Note at 12.5 kHz the -6 dB beamwidth is still 40° wide. In practice above 10 kHz the modal behavior, inherent in any compression driver, causes the output to be more randomized and results in the beamwidth being wider (as is seen in the PD743 horizontal beamwidth curve shown in the Appendix.)

Figure 8: Polar response of two 90° dispersion signal sources spaced 1 inch apart. (From outside to inside at 25° off-axis: 8, 10, 12.5, and 16 kHz.)



Spacing the two apertures 1 inch apart with a traditional large format compression driver is difficult, or completely impossible due to the large outside diameter of these drivers — typically between 6.5 and 10 in.). Figure 9 shows that for a fixed depth of combining throat, the included angle between the two drivers is large. Dimensions “D1” and “D2” show the difference in arrival time of the two “sides “ of the wavefront at the aperture. A shorter throat increases the angle, and produces more interference. A longer throat is more desirable, but the length of the throat is constrained for many reasons, including the requirement of a specific location for the compression drivers in the throat of the co-axial system.

Figure 9: Compared to previous compression drivers, the 2430 minimizes the included angle between compression drivers on a combining throat and minimizing path length difference (D2 minus D1).



The Solution for Coherent Summation:

The solution for combining the output of two compression drivers was clear with the introduction of the 2430H large format driver. The 2430H is only 108 mm (4 1/4 in.) in diameter, however ferro-fluid cooling provides the 2430H with the same output and power handling as industry standards like the 2447 and 2451. Improvements in the design of the magnetic circuit resulting from advances in computerized finite element analysis provide the same sensitivity as traditional JBL compression drivers.

In the PD700 series an aluminum cast throat section combines the output of the two horizontally arrayed 2430 drivers. Referring back to figure 9, the included angle between the primary axis is reduced to only 8.5°. This reduces the offset in arrival of the wavefront at the aperture (D2 minus D1) to 3.5 mm (0.14 in.) which is 63 μs. As a result, an acceptable 57° of phase variation occurs at 16 kHz.

The aperture of this throat section is then loaded by a rigid fiberglass constant directivity horn. Note that in the horizontal plane the true "slot" of the horn, where the horizontal width is minimum, is 45 mm (1 3/4 in.) in front of the aperture of the dual driver throat. This short section serves to integrate the output of the two drivers further, as the wavefronts combine.

The final performance of the PD743 high frequency assembly is shown as follows:

Figure 10 is the raw, unprocessed, frequency response and impedance curve of the high frequency section. Note the smooth frequency response throughout the entire usable piston band of

the compression driver. The response is admirably free of all performance aberrations to a frequency greater than 11 kHz.

Figure 11 shows the horizontal off-axis response of this same horn. These high resolution curves further demonstrate how the two compression driver high frequency horn truly behave as a single unified signal source to beyond 16 kHz.

Figure 10: PD743 raw high frequency response (2V/1m sensitivity on left scale), and impedance (in ohms, shown on right scale).

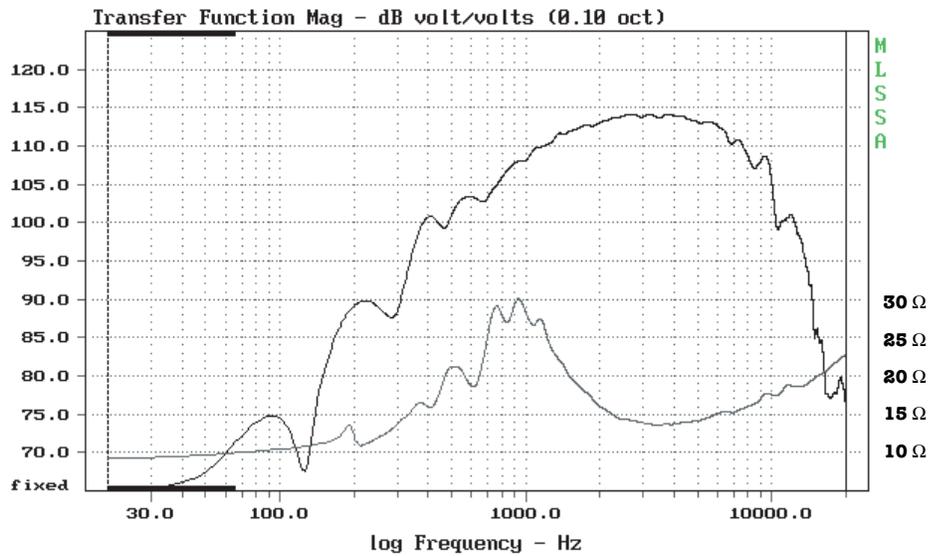
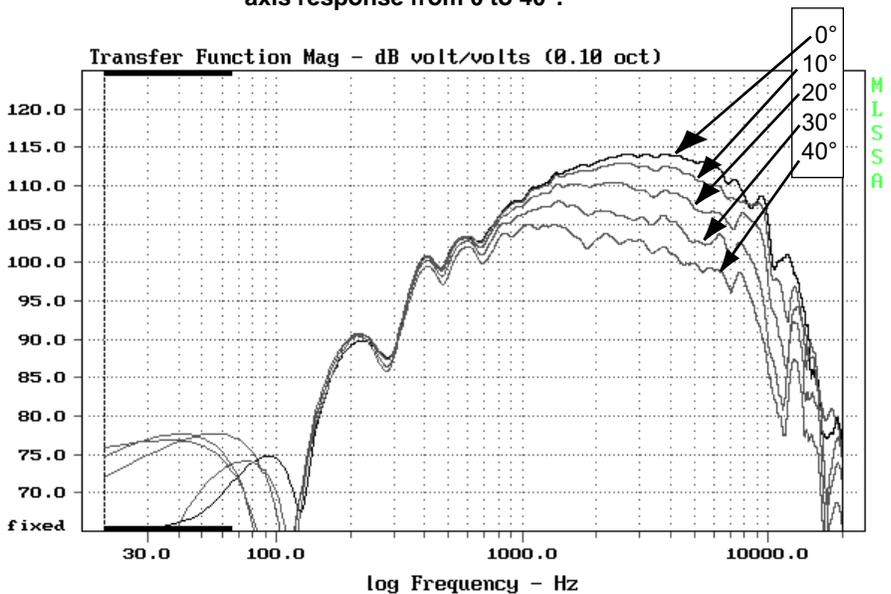


Figure 11: PD743 raw high-frequency horizontal off-axis response from 0 to 40°.



Optimized Signal Processing For Smooth Crossover Transitions:

Perhaps the most important, and overlooked, final step in the engineering of a loudspeaker, is to determine the signal processing to provide optimal performance for each individual enclosure, and for arrays. An optimized response for each enclosure provides the audio professional with a clean “template” for quickly tuning the overall system once it is installed. For this reason JBL provides template tunings for the PD700 series. Tuning are available for popular processors such as JBL DSC-260, BSS Soundweb and dbx Driverack.

Since the PD700 series are equally symmetrically well-behaved through horizontal and vertical crossover regions, an unusual degree of freedom exists in crossover design. In a non-coaxial system, where the high frequency horn is displaced to one side of the midrange horn, in order for the crossover not to lobe off-axis, the two pass bands must be perfectly in phase and at a level of -6 dB at the crossover point.² For a symmetrical loudspeaker, the crossover region may be manipulated to optimize the system response both on and off axis to achieve equally consistent frequency response at all angles, on- and off-axis, horizontally and vertically.³

How is the optimal performance achieved? Typically there are 8 variables available in a digital loudspeaker processor: Crossover frequency; High pass filter slope; High pass filter type; low pass

slope; low pass filter type; interchannel delay; polarity and all-pass filtering. Each of these variables were carefully optimized to yield the results shown below.

The filter slopes and alignments allow the interaction between the pass-bands to be controlled. By determining the correct amount of interaction to occur at each frequency, the beamwidth and directivity interaction between the pass-bands can be adjusted to assume the characteristic of either pass-band at each frequency.

As an example of this result, Figure 12 shows a high resolution frequency response plot of the processed midrange, high frequency, and the net system response for a PD743 . Figure 13 shows three horizontal beamwidth curves: raw PD743 midrange section beamwidth, raw high frequency beamwidth, and the overall horizontal beamwidth of the system with the optimal processing.

Figure 13: PD743 horizontal beamwidth contributions, with recommended signal processing.

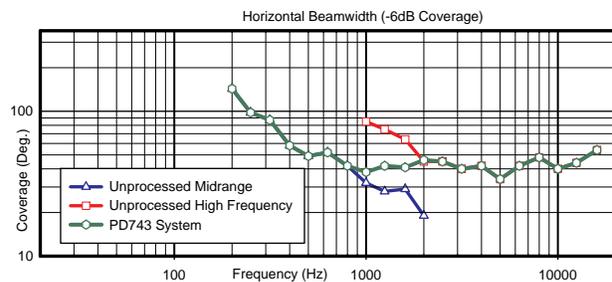
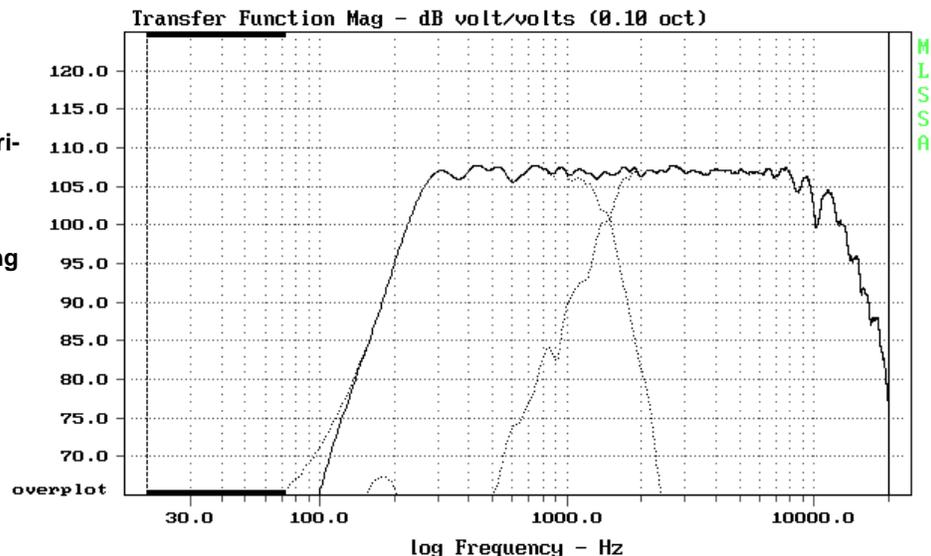


Figure 12: PD743 contribution from midrange and high frequency bands to system frequency response, using recommended signal processing.



Finally the Appendix shows the PD743 system beamwidth curves, Directivity and Q, as well as horizontal and vertical normalized off axis response. These measurements were made using the recommended parameters for a BSS Soundweb. The “.SDF” files are available at www.jblpro.com, along with setting for other popular controllers.

These settings provide the system designer with a “clean” template response for the PD700 series – flat frequency response, and optimized cross-over performance. Any additional equalization required can easily be applied as “input filters” – filters located before the processing of the mid and high

frequency pass bands. This maintains the optimal performance through the mid-high crossover. The low frequency crossover parameters provided may also serve as a useful baseline, but will likely vary depending on the actual low frequency system specified.

Additionally, various processor parameter sets are available for typical arrayed configurations of PD700 series enclosures. These parameter sets compensate for coupling of the midrange horns at lower frequencies, and high frequency air absorption losses in various PD700 series array configurations. See www.jblpro.com for details.

Conclusions:

The goals of the JBL Professional PD700 series were to maximize the application and utility of each enclosure in the product line, to allow the audio professional to design effective arrayed systems which meet the needs of the venue.

This goal was achieved by first examining performance limitations of existing solutions, then systematically eliminating these limitations.

The resulting PD700 series enclosures are dual midrange, dual high-frequency co-axial systems with maximum output 6 dB greater than previous systems. The output of each transducer combines coherently without any interference, increasing maximum SPL by 6 dB. The square faced, dual trapezoidal enclosures are rotateable and easily arrayed. Optimized signal processing is provided to minimize the time required to tune the system after it is installed.

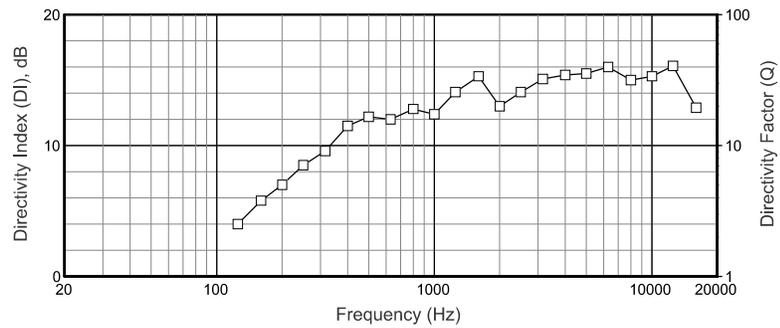
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2. J. Vanderkooy & S. P. Lipshitz, “Power Response of Loudspeakers with Noncoincident Drivers – The Influence of Crossover Design”, JAES, vol. 34, pp. 236-244 (April, 1986)
3. J. D’Appollito, “A Geometric Approach to Eliminating Lobing Error in Multiway Loudspeakers”, presented at the 74th Convention of the AES, JAES (abstracts), vol 31, no. 12, p 968 (Dec 1983), Preprint 2000.

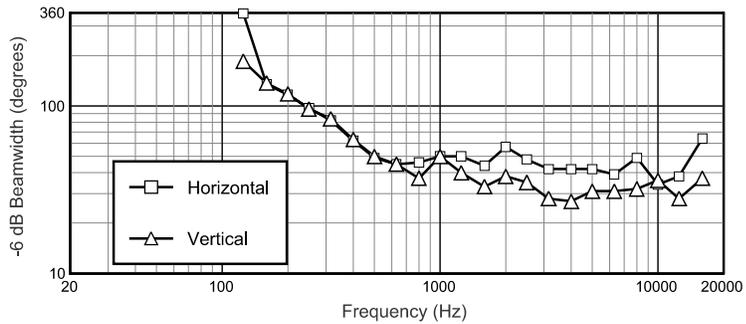
Appendix:

For reference, the following additional frequency response curves are provided for the PD743 system:

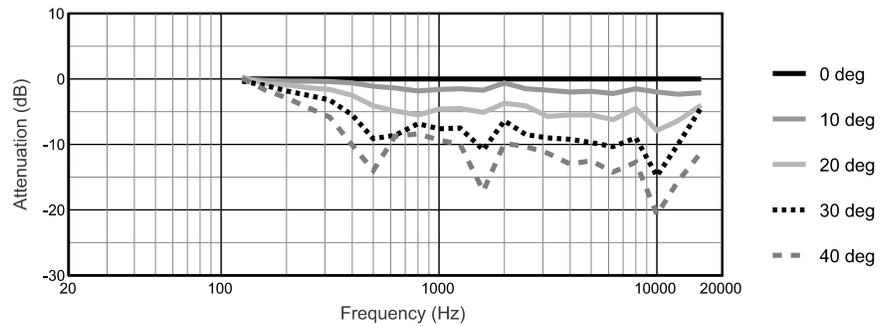
Directivity Index and Q:



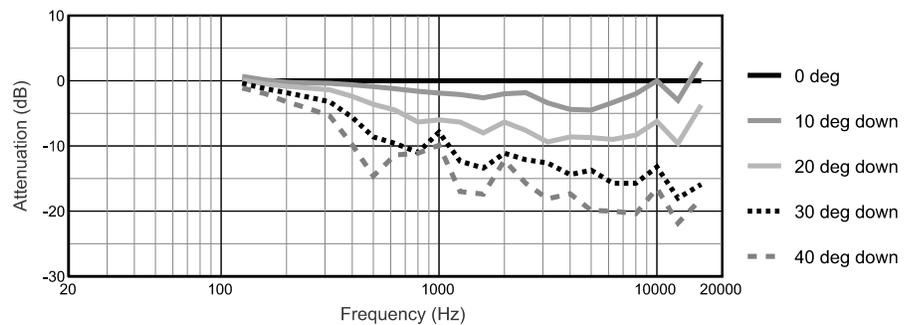
Horizontal and vertical beamwidth:



Horizontal normalized off-axis response:



Vertical normalized off-axis response:



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