Part 1

Designing a Passive Two Way Open Baffle Speaker System

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By Martin J. King, 09/15/07 (revised 10/05/22)

Introduction :

A search of the Internet will reveal that there are a number of commercially available open baffle, hence forth abbreviated as OB, dipole speaker systems available in the audio marketplace. Offerings such as Seigfried Linkwitz's Orion[(1)], John Kreskovsky's NAO[(2)], and Paul Hilgeman's Ronin[(3)] can all be characterized as floor standing narrow baffle dipole speaker systems. Each features active crossovers and EQ filters requiring at least two amplifiers. These are all very sophisticated well engineered designs that allow the use of a narrow baffle while still producing satisfying bass output. The key to these designs is the use of active crossovers and EQ filters to produce sufficient low frequency output.

Some examples of OB speaker systems that use passive crossovers are Danny Richie's OB-5 and OB-7[(4)], the Jamo R 909[(5)] and Hawthorne Audio's Solo[(6)]. These are also narrow, at least when considering some of the woofer diameters, OB speaker systems that claim bass performance down into the 25 - 30 Hz range. Being passive crossover designs, these speakers do not have requirements for sophisticated electronic filters and multiple amplifiers. Instead they rely on the acoustics of the baffle and a passive crossover to generate a balanced SPL frequency response. While the cost of multiple amplifiers is no longer a factor in these designs, the most expensive of all the OB speakers mentioned is the Jamo R 909 speaker system which on sale is still $7500 (the list price is approximately $13,000).

Even though I have not heard any of these OB speaker systems, I am sure the performance of each is outstanding and easily justifies the cost. But the combination of a baffle's acoustic design and a passive crossover, as used in the Jamo R 909, to tune the bass response was just too intriguing for me not to try and understand the trade-offs. Reading the online copy of a Jamo R 909 white paper started me thinking about how to achieve this simple yet elegant design concept. As a first step I have performed a design study, using some of the concepts learned from studying the Jamo white paper and owner's manual, for a passive two way OB system that is very modestly priced. This design study is discussed on the following pages. The next logical step would be to design a bigger all passive crossover three way OB speaker system. That may be the topic of a future study, project, and document.

DIYer Designs on the Net :

Looking around the Internet for DIYer designs of OB speakers yields a wide variety of different baffle sizes, baffle shapes, number of drivers, types of drivers, and passive or active crossovers being used. The level of sophistication in the design process spans from a trial and error design based on experience/experimentation all the way up to a design based completely on computer simulation predictions of SPL response curves. Both methods work and can generate finished OB speaker designs with exceptional performance. The design of an OB speaker system can be as quick and easy as constructing a temporary baffle from cardboard, listening to the response, and making immediate adjustments to address shortcomings in what the designer/builder hears. Quick, easy to build, and cheap are all appealing attributes of OB systems for a lot of DIY speaker builders.

An OB speaker system is a fairly forgiving design where probably the worst possible outcome is disappointing bass performance. But additional bass response can be added later with a dedicated subwoofer so a fix is fairly easy. The drivers produce SPL frequency responses consistent with manufacturer's specification sheets without any interaction with a tuned enclosure. The baffle itself tends to only roll off the driver's lowest frequencies starting at a frequency value determined by the physical size and shape of the baffle. Without the potential for mistuning an enclosure, the resulting booming or anemic bass performance problems of boxed speakers are avoided.

A compromise position between a completely experimental design method and a completely computer simulation based design method is the use of tools like the EDGE(7) computer program. The EDGE program helps define the influences of the baffle's size and shape on the system's low frequency response. Using a baffle response calculator, like the EDGE, does not factor in the influence of the driver's response so it is only one piece of the puzzle. Sometimes the other puzzle pieces are neglected when the DIY designer focuses solely on the calculated baffle response. Using programs like the EDGE requires the designer to somehow sum the baffle's response with the speaker's response to generate the system's response. In my opinion, too much emphasis is sometimes placed on the calculated baffle response curves without considering the complex summation that needs to occur to produce the complete system response.

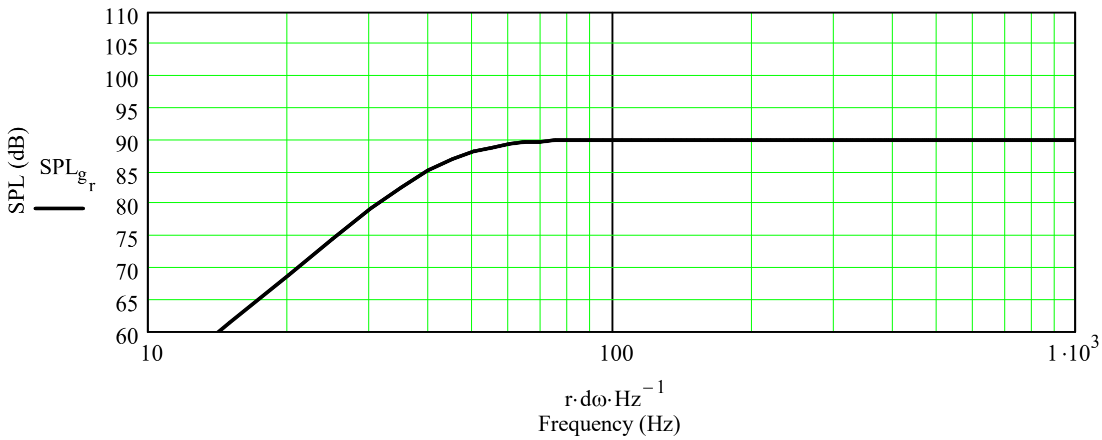
I really like full range drivers and the lack of a crossover in the midrange frequencies, so I am going to slant this approach to the use of full range drivers as wide band devices with the bass reinforced by an additional driver. In my opinion, there is no affordable single full range driver available that can be mounted in a reasonably sized OB speaker system and still reproduce balanced bass, midrange, and treble responses. While the midrange can be handled nicely by a single full range driver in an OB, one end or maybe both ends of the audio spectrum will be compromised. Therefore, for this study the bass performance requirement will be met by using a woofer driver that is crossed over between 100 and 200 Hz to the full range driver.

Selecting Drivers :

In the design of multi-way OB speaker systems using passive crossovers, I have not seen a method presented for selecting bass and full range drivers that will assure a smooth and balanced SPL response. Therefore, a method for selecting the appropriate bass driver for a particular baffle size and shape so that the combined efficiency matches the full range driver's midrange efficiency will be presented. The starting point is the full range driver; the efficiency of the midrange frequencies sets the requirement for the entire system SPL response.

To begin the design process, we need to first define the desired end result. For an OB speaker system the bass will roll-off at a rate of 18 dB/octave, this is the sum of a 12 dB/octave roll-off for the driver and a 6 dB/octave roll-off for the open baffle. If we assume an efficiency target, a goal function can be constructed. Figure 1 depicts a 90 dB/W/m goal function, tuned to 45 Hz, which will be assumed for this sample OB design. This 90 dB response is to be achieved at a one meter distance along the axis of the full range driver. The full range driver will be located 32 inches above the floor which is approximately at ear level when seated. There is nothing magical about this goal function other then the efficiency being consistent with the selection of the full range driver. A different efficiency, tuning frequency, or listening position could just as easily have been selected. The challenge is to design a baffle that couples with a woofer and will produce the defined 90 dB efficiency and the desired low frequency roll-off.

Figure 1 : The OB Speaker System SPL Goal Function



By setting the goal function's efficiency between 88 and 92 dB, many smaller 3", 4", and 5" full range drivers are excellent candidates for an OB design. Table 1 presents some options from the Fostex family of full range drivers.

Table 1 : Manufacturer's Specifications for Fostex Drivers

Driver	FE103E	FE107E	FE108EZ	FE126E	FE127E	Units
fs	79.5	80.0	77.0	70.0	70.4	Hz
Re	7.45	7.60	6.80	6.90	6.50	ohm
Qed	0.40	0.45	0.32	0.27	0.50	-
Qmd	2.87	2.56	7.79	2.96	3.33	-
Qtd	0.36	0.38	0.30	0.25	0.43	-
Vad	6.90	5.95	5.70	9.95	9.90	liter
BL	4.42	4.70	5.20	5.92	4.14	N/amp
Xmax	0.35	0.35	0.28	0.35	0.67	mm pk-pk
SPL	89	90	90	93	91	dB/W/m
Unit Cost	38.20	40.45	88.15	42.75	45.00	US $'s

Other Possible Fostex Drivers : FE83E, FE87E, FF85K, FF125K, F120A, F200A

Reviewing the drivers listed in Table 1, and recognizing that a woofer will be used to eliminate the need to produce bass frequencies, the manufacturer's Thiele / Small parameters for the full range drivers are no longer as important in the design process. There are three drivers shown in Table 1 that have efficiencies of 90 dB/W/m. Since low cost was also a goal of the design, I selected the FE103E for this study.

Having selected the full range driver and defined the target SPL and bass roll-off, requirements for the bass driver can now be considered. One requirement is that the efficiency of the woofer must be greater than the design goal of 90 dB/W/m. Consider this efficiency requirement for a minute. If the bass driver were mounted in an infinite baffle a 90 dB/W/m efficiency would be adequate. But as the baffle size decreases, the support for the bass frequencies drops leading to a requirement that the woofer efficiency must be significantly higher than the 90 dB goal function. For a passive crossover OB system, the smaller the baffle the more efficient the woofer must be to satisfy the SPL goal function. This requirement for increased woofer efficiency can be handled by multiple woofers in parallel or by using a single larger diameter pro-audio woofer. I selected the second option for the woofer, a larger diameter pro-audio woofer will have the required efficiency, a lower cost, and in the end I believe it will lead to a simpler baffle design.

For this study, I focused on three of the Eminence pro-audio woofers that spanned a range of Qts values typically used in DIYer OB speaker systems. All three are significantly more efficient than the specified 90 dB/W/m goal function. The manufacturer's Thiele / Small parameters for the three woofers are summarized in Table 2. The basic difference between these three models of Eminence woofers is the magnet, as the magnet size and strength increases the Qts decreases while the price increases. This is a very simplistic characterization but I believe it is a reasonable assessment of the important trade-offs between the three drivers.

Table 2 : Eminence 15 " Woofers

Eminence	Alpha 15A	Beta 15A	Gamma15A	Units
fs	41.0	35.0	33.0	Hz
Re	5.88	6.32	5.98	ohm
Qed	1.53	0.63	0.32	-
Qmd	7.23	8.10	5.13	-
Qtd	1.26	0.58	0.30	-
Vad	260.5	334.6	314.1	liter
BL	7.70	11.5	17.2	N-amp
Xmax	3.8	4.0	3.0	mm pk-pk
SPL	97.0	98.2	98.6	dB/W/m
Unit Cost	58.19	67.89	77.59	US $'s

All three Eminence woofers were simulated in combination with the Fostex FE103E full range driver and a passive crossover network. After iterating each design many times, the pairing of the Fostex FE103E and the Eminence Alpha 15A provided the closest match with the SPL goal function and the smallest baffle dimensions. By examining the behavior of this design in detail, an understanding of why it works can be gained. Then substituting each of the other two woofers into the design, potential trade-offs required to provide similar low frequency performance levels can be discussed.

Figure 2 shows the final baffle layout for the Fostex FE103E full range driver paired with the Eminence Alpha 15A woofer. The baffle is 20" wide and 38" tall. The woofer is centered 10" above the bottom edge of the baffle. The full range driver is 32" above the bottom edge of the baffle and shifted 2" off center. Recognize that this OB design would need to be constructed in mirror image pairs.

Figure 3 is the calculated system SPL response at 1 m on the axis of the full range driver. The red curve is the calculated response and the black curve is the SPL goal function. The response in Figure 3 assumes ideal 2nd order crossovers, crossovers with real components interacting with the driver's electrical impedances will be shown later. The other interesting feature of Figure 3 is the apparent 92 dB/W/m efficiency of the Fostex FE103E driver. For this study, assume that this portion of the SPL response will be 2 dB lower matching the manufacturer's data sheet. Factoring in these two observations, it is clear that the design follows the SPL goal function closely.

Figure 2 : Woofer and Full Range Driver Locations on a 38" x 20" Open Baffle
Axis Dimensions are Meters

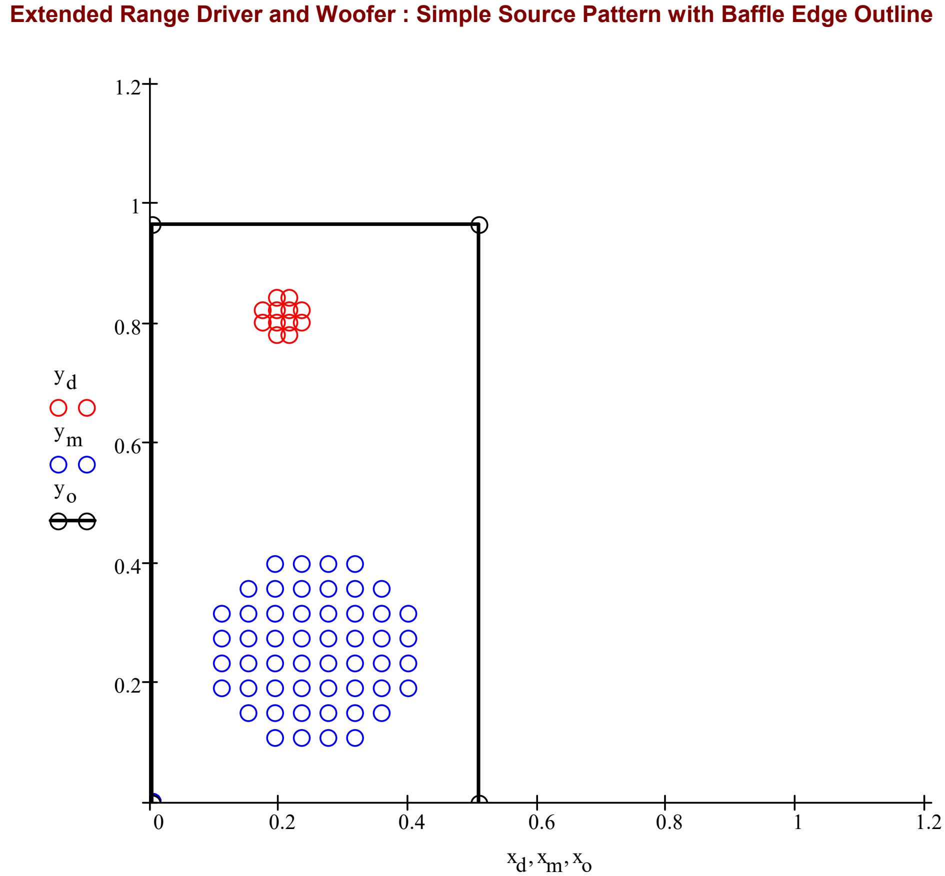
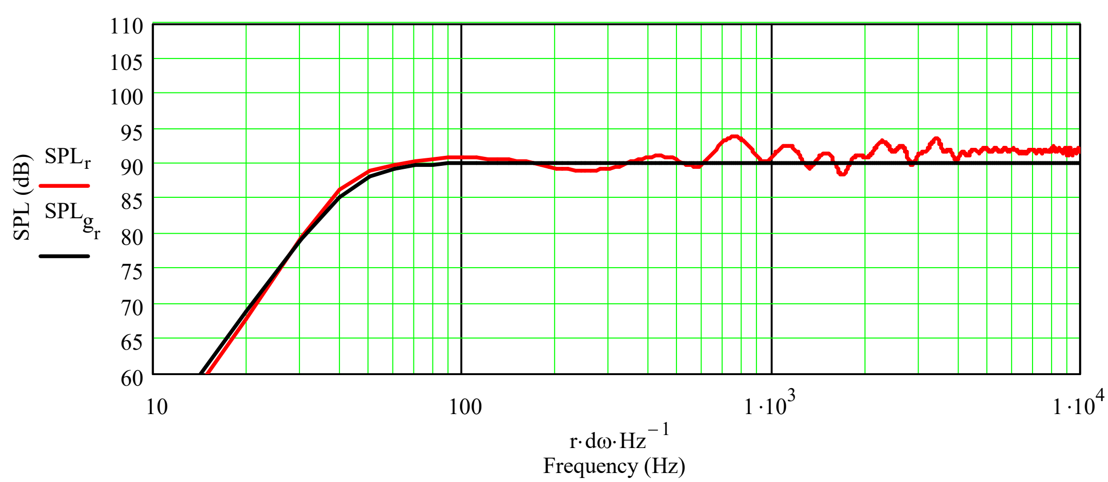


Figure 3 : Preliminary Calculated System SPL Response



Getting the Bass Right :

To understand the contributions that the woofer and the baffle are each making to the system's low frequency response, you need to separate the contributions and show each individually superimposed over the SPL goal function. Figure 4 shows the Eminence Alpha 15A calculated SPL response in an infinite baffle (dashed blue curve), in an infinite baffle with a floor reflection (solid red curve), and the SPL goal function. Compared to the SPL goal function, the calculated SPL response for the woofer in an infinite baffle with a floor reflection is almost +10 dB more efficient at low frequencies. The other interesting feature of the two calculated curves is the gentle roll-off that starts above 100 Hz, this is due to the directional behavior of the 15" diameter woofer. The downward sloping response is produced by the off axis listening position, remember the listening position is specified at the height of the full range driver. If the floor was removed and the listening position changed to be on the axis of the woofer, the anechoic infinite baffle response curve would be generated. Finally, at approximately 500 Hz a floor bounce cancellation is also seen. A mirror image of this OB geometry can be visualized below the floor boundary condition creating this floor bounce cancellation. Figures 5 and 6 complete the bass response story.

Figure 4 : Woofer Infinite Baffle Response Curves

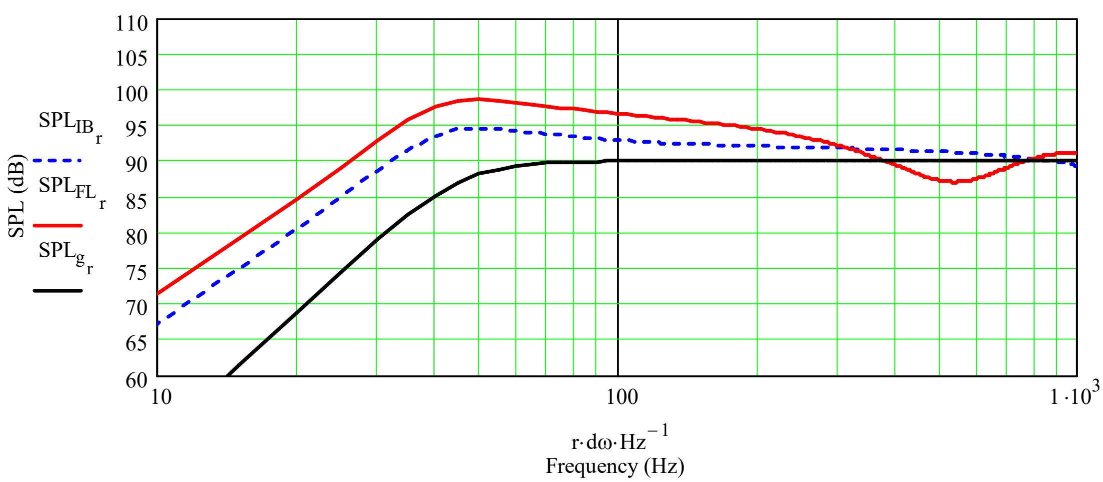


Figure 5 adds the influence of an ideal 2nd order low pass crossover. Shown are the calculated infinite baffle SPL response with the floor reflection from Figure 4 (dashed red curve), the 200 Hz low pass crossover (dashed blue curve), the combined SPL response (solid red curve), and the SPL goal function.

Figure 6 adds the influence of the finite baffle size and shape. The combined SPL response curve from Figure 5 (dashed red curve), the finite baffle response curve (dashed blue curve), the final combined woofer bass response curve (solid red curve), and the SPL goal curve are all shown.

Figure 5 : Woofer Infinite Baffle Response Curves
w/ Floor Reflection and Second Order Crossover

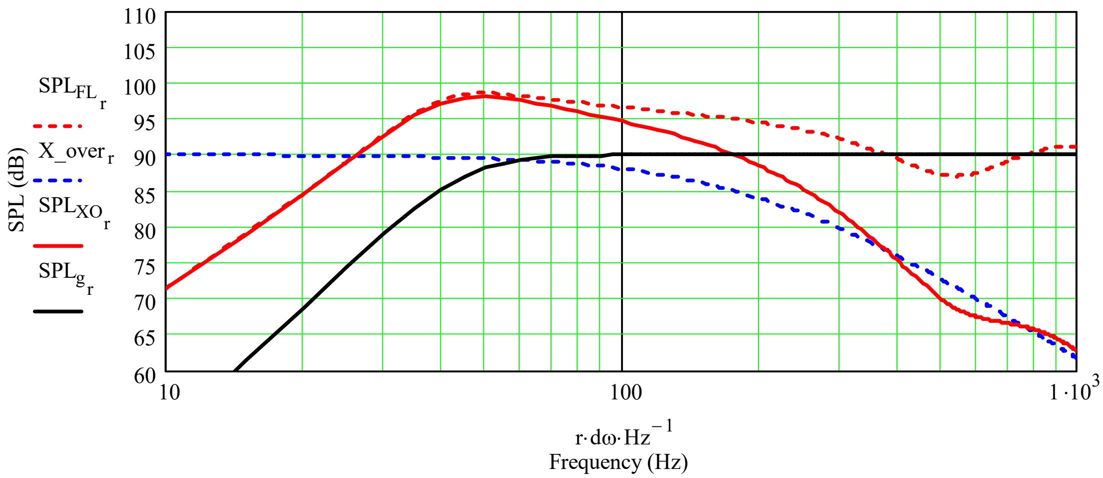
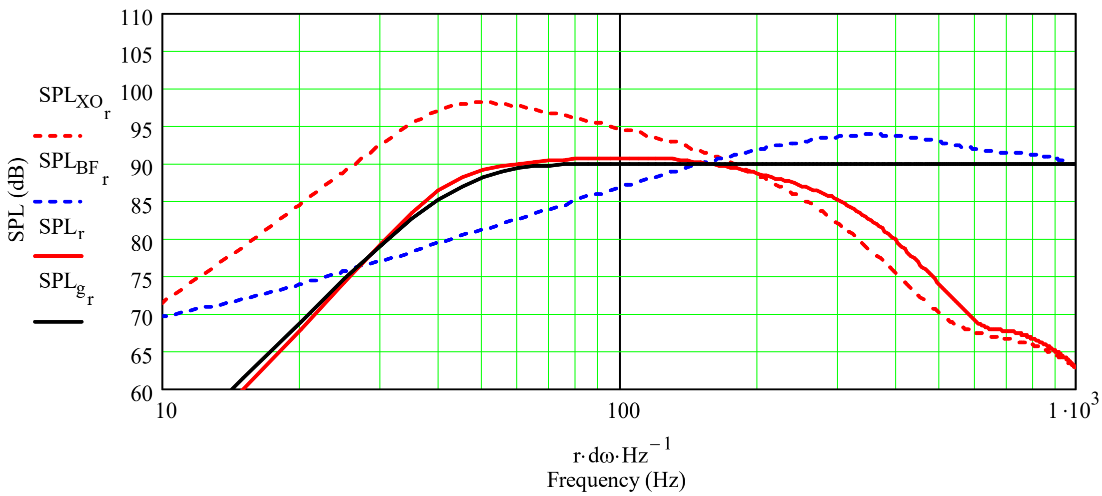


Figure 6 : Woofer Infinite Baffle Response Curves
w/ Floor Reflection, Second Order Crossover, and Finite Baffle Size



The curves shown in Figure 6 have a number of interesting features. Starting with the dashed red curve, this is the infinite baffle woofer response curve from Figure 5 including a second order crossover at 200 Hz. The dashed blue curve is the finite baffle component of the response similar to what would be calculated by the EDGE program. Combining these two response curves, taking into account the phases which are not shown, produces the final woofer SPL response curve depicted by the solid red curve The final woofer response closely tracks the SPL goal function.

In Figure 6, also notice the intersection of the two dashed curves at 165 Hz. Below 165 Hz, the finite baffle attenuates the rising woofer response bring it in line with the SPL goal function. Above 165 Hz, the hump in the finite baffle response is used to extend the effective crossover frequency to approximately 400 Hz. By setting the actual crossover point below the baffle response hump, a peak rising above the SPL goal function was also avoided. Based on the solid red curve, the high pass crossover frequency for the full range driver can be set higher than the 200 Hz frequency used for the low pass crossover.

So far, the low frequency portion of the design has been optimized for the Eminence Alpha 15A woofer. But two other woofer choices were also listed in Table 2 with lower Qts values. Figure 7 shows the low frequency responses of all three woofers with the same baffle and crossover design. Reviewing the three plots it is seen that as the Qts decreases the low frequency response also decreases. The only way to regain low frequency output is to increase the baffle size which effectively shifts the dashed blue line in Figure 6 to the left. Then to regain control of the rounded hump originally between 100 and 200 Hz, a lower crossover frequency is required. The more expensive woofer drivers like the Beta 15A and Gamma 15A with lower Qts values require larger baffles, a lower crossover point, and will probably still not extend as low as the less expensive Alpha 15A.

One objection heard often with respect to higher Qts drivers in OB designs is that the bass transient response will ring and produce a bloated one note bottom end. Figure 8 shows the impulse responses for the three Eminence drivers in the OB design from Figure 7. Again there is not much difference in the shape of the three curves. The only significant difference is the increasing length of the transient response with increasing Qts, but since the Alpha 15A woofer extends lower in the frequency domain it should also have a slightly longer transient response in the time domain. There is no evidence of excessive ringing bass response from any of these three drivers. Once again, the better OB low frequency performance is achieved with the higher Qts Eminence Alpha 15A woofer.

Figure 7 : SPL Response Comparison for the Three Eminence 15” Woofers

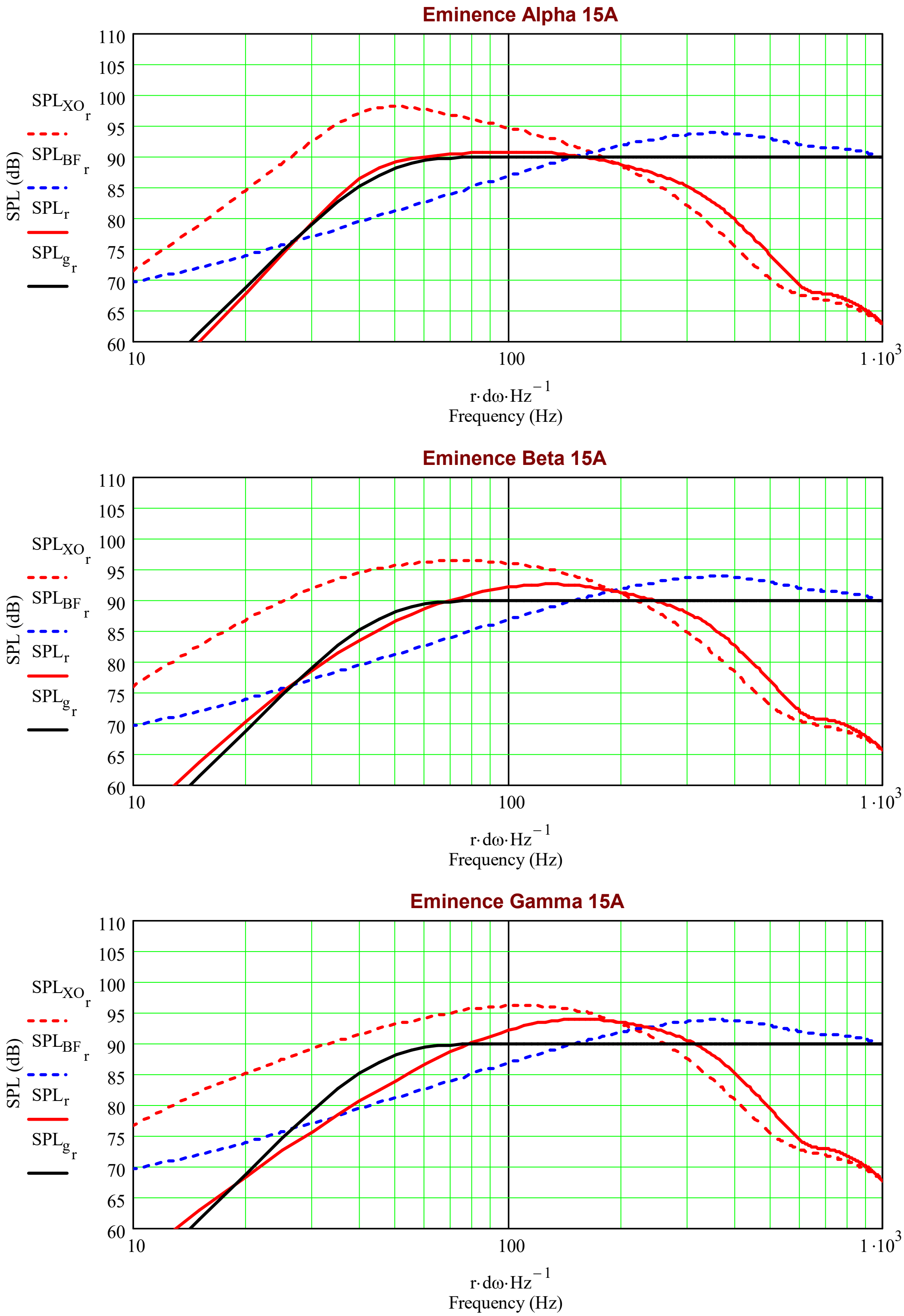
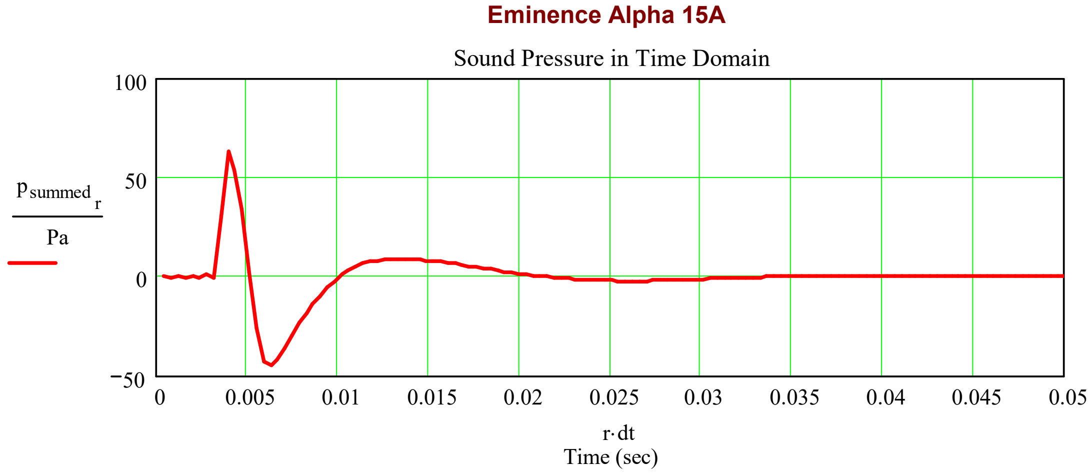
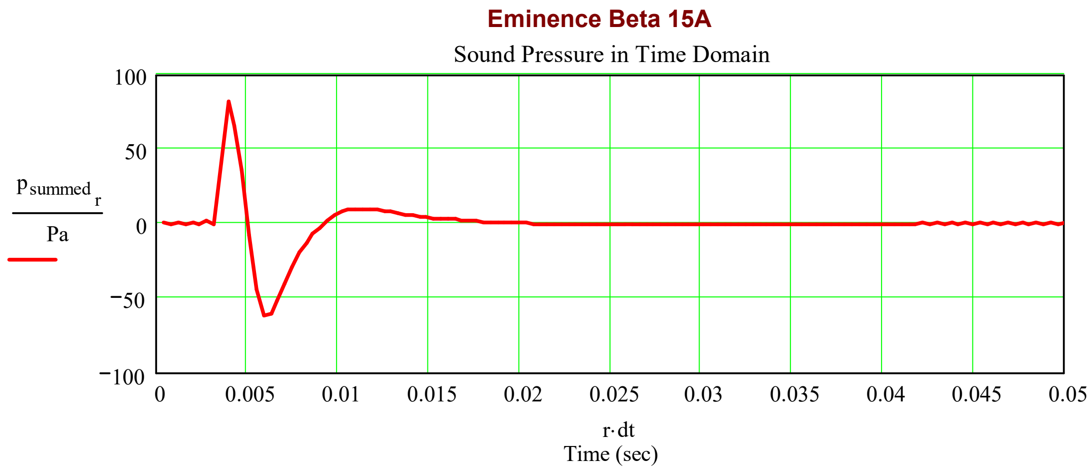
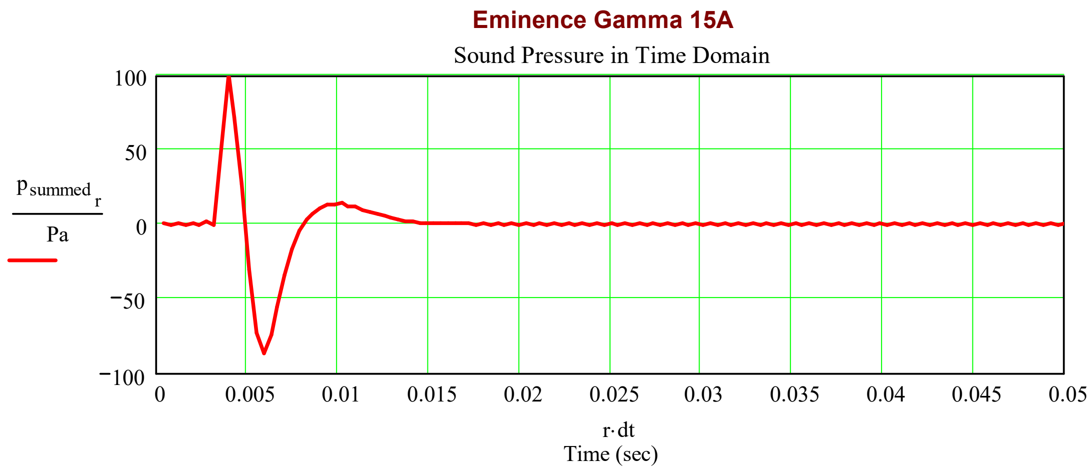


Figure 8 : Impulse Response Comparison for the Three Eminence 15” Woofers







Crossing Over to the Full Range Driver :

The full range driver provides the rest of the audio spectrum. A high pass crossover is used to filter out the bass frequencies and the associated large deflections. To understand the different contributors to the full range driver's SPL response, a similar set of plots are presented. Figure 9 shows the full range driver's calculated SPL response in an infinite baffle (dashed blue curve), in an infinite baffle with a floor reflection (solid red curve), and the SPL goal function. The ripples that are seen in the solid red curve are generated by floor reflections.

Figure 9 : Full Range Driver Infinite Baffle Response Curves

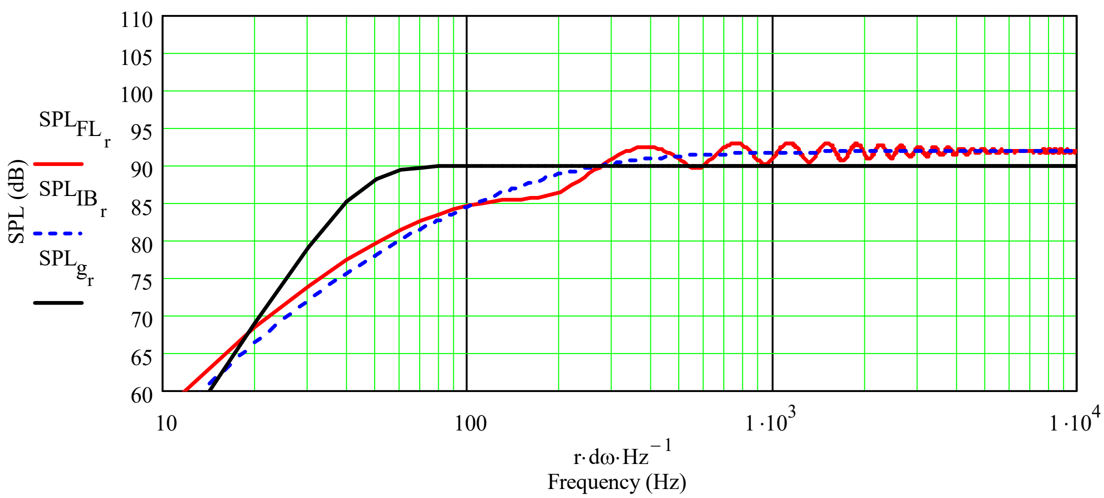


Figure 10 : Full Range Diver Infinite Baffle Response Curves
w/ Floor Reflection and Second Order Crossover

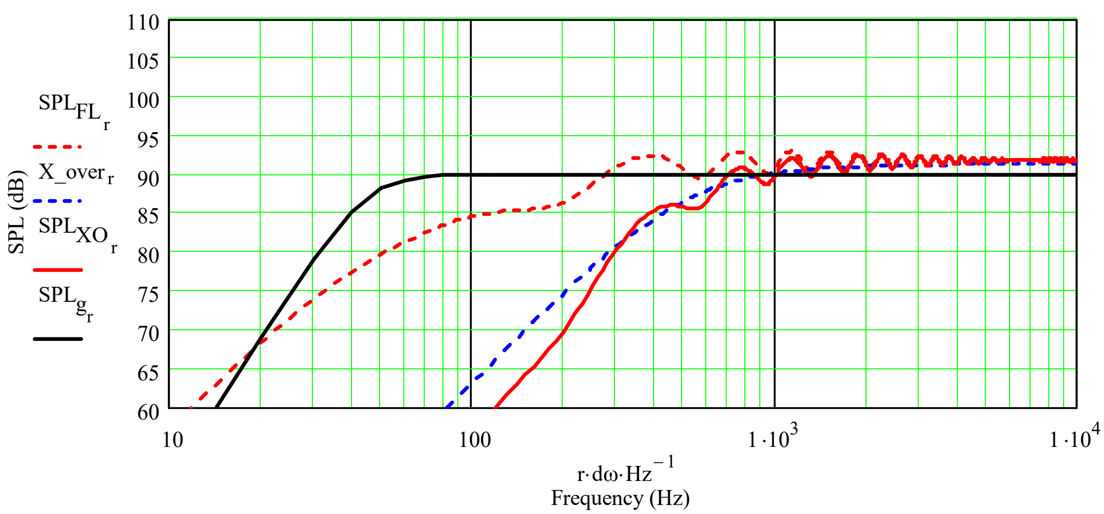
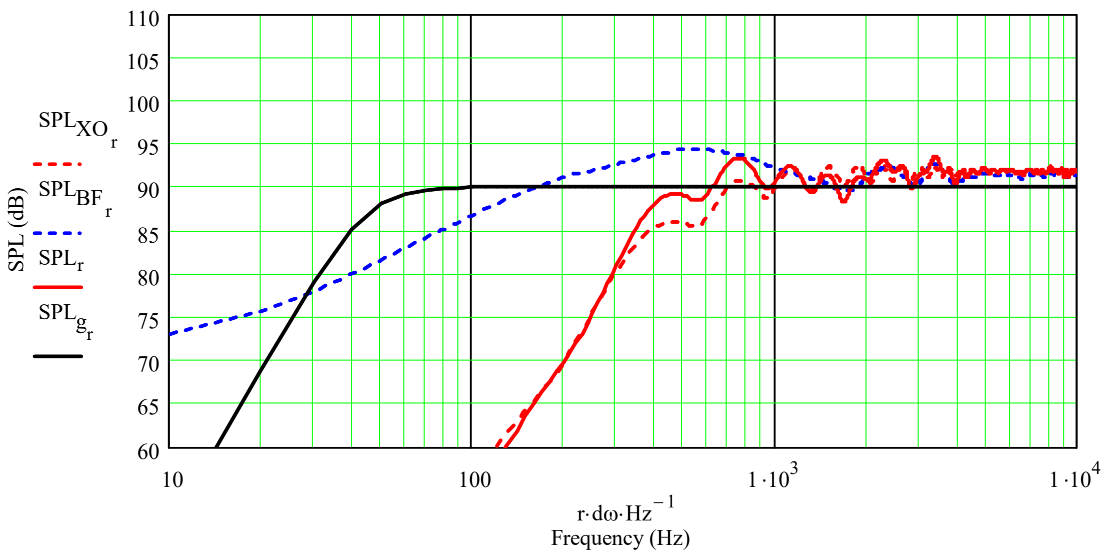


Figure 10 adds the influence of an ideal 2nd order low pass crossover. Shown are the calculated infinite baffle SPL response with the floor reflection from Figure 9 (dashed red curve), the 500 Hz high pass crossover (dashed blue curve), the combined SPL response (solid red curve), and the SPL goal function.

Figure 11 adds the influence of the finite baffle size and shape. The combined SPL response curve from Figure 10 (dashed red curve), the finite baffle response curve (dashed blue curve), the final combined full range driver response curve (solid red curve), and the SPL goal curve are all shown.

Figure 11 : Full Range Driver Infinite Baffle Response Curves
w/ Floor Reflection, Second Order Crossover, and Finite Baffle Size



In Figure 11, notice again that the hump in the baffle response (dashed blue curve) is used to extend the full range drive's response lower in frequency. The hump in the finite baffle response curve lowers the effective crossover frequency to approximately 400 Hz. By setting the actual crossover frequency point above the baffle response hump, a peak rising above the SPL goal function was avoided again. Also recognize, as stated earlier, that the significant ripples in the full range driver's calculated response are due to floor reflections and are not properties unique to an OB design.

Design of the Passive Crossover :

As defined above, the low pass crossover is 2nd order at 200 Hz and the high pass crossover is 2nd order at 500 Hz. Due to the rounded hump in the baffle's response plot, the effective 2nd order crossovers are both at approximately 400 Hz. The crossover parts list is provided below in Table 3 with the schematics shown in Figure 12.

Table 3 : Passive Crossover Parts List

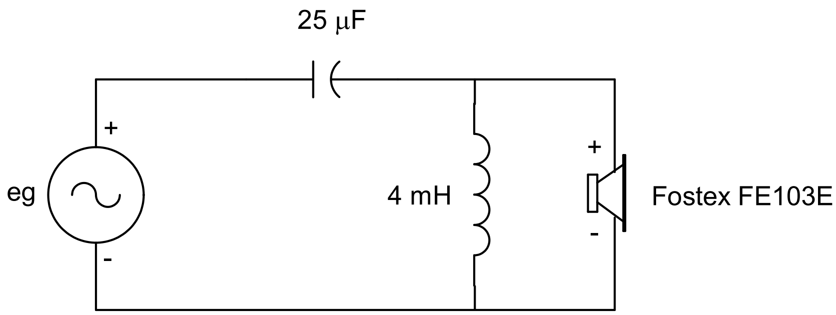
High Pass

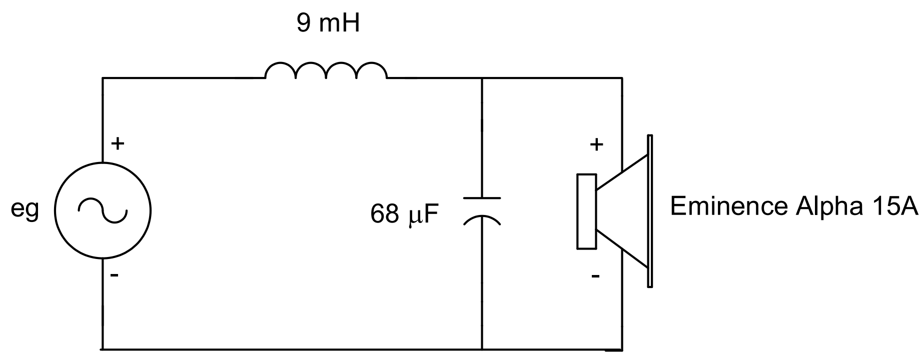
Component	Value	Parts Express ID	US $'s
Capacitor	24 uF	027-586	8.25
Inductor	4 mH	266-922	19.72

Low Pass

Component	Value	Parts Express ID	US $'s
Capacitor	68 uF	027-608	18.43
Inductor	9 mH	266-944	23.44

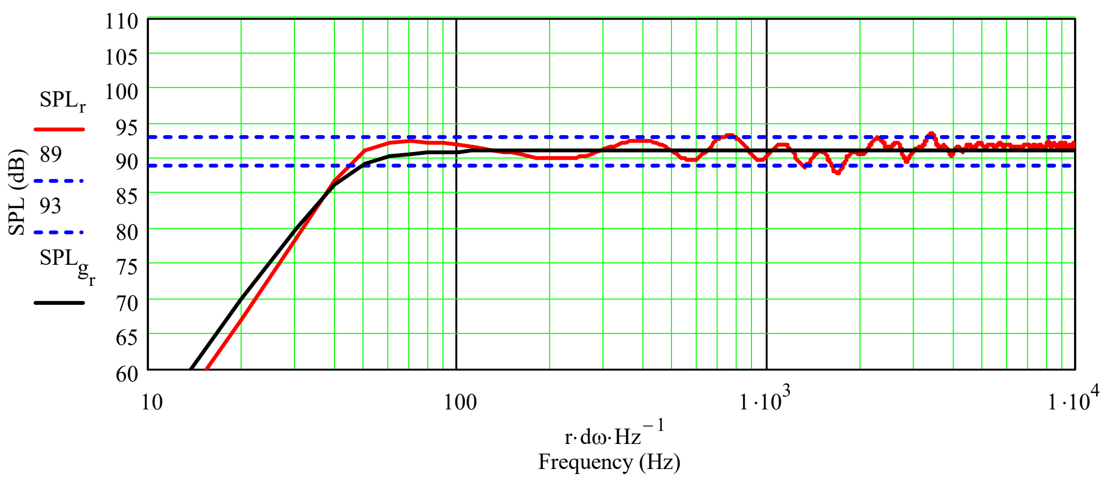
Figure 12 : Crossover Schematics





Substituting the actual crossover components, including the DC resistances of the inductors, the final system SPL response curve is shown in Figure 13. In this plot the goal function efficiency has been increased to 91 dB and dashed blue lines are included to show +/- 2 dB offsets from the goal function. This SPL response curve represents the final result for this study.

Figure 13 : Final Calculated System SPL Response



Final Cost Breakdown :

Item	Quantity	US $'s
Fostex FE103E	2	76.40
Eminence Alpha 15A	2	116.38
Inductor – 4 mH	2	39.44
Inductor – 9 mH	2	46.88
Capacitor – 24 uF	2	16.50
Capacitor – 68 uF	2	36.86
4' x 8' Sheet of Plywood	1	55.00
Total Cost	-	387.46

Conclusions :

The biggest challenge for OB speaker systems using passive crossovers is to achieve adequate bass output from a reasonably sized baffle. To achieve this goal you need to recognize that the driver, baffle, and low pass crossover are a system that needs to be optimized to meet a low frequency response goal. I believe that crossing over at a lower frequency helps with the optimization and avoids potential problems in the critical midrange frequencies. Because this is an optimization challenge, one cannot just swap out low frequency drivers in any OB and make final judgments about the suitability of a particular driver's characteristics for OB speaker loading. This is similar to blindly swapping drivers in a Bass Reflex or Acoustic Suspension enclosure without regard to the system alignment. A driver, baffle, and crossover should be designed to combine and form an optimized alignment.

I believe the main cause for weak bass output in OB speaker designs using passive crossovers is low Qts woofer drivers and/or efficiency mismatches with the full range or midrange driver. A woofer driver needs to be significantly more efficient than the full range or mid range driver to make up for the falling low frequency response exhibited by a reasonably sized baffle. A low Qts driver just compounds this problem by also having a falling low frequency response. A low Qts driver will need to be extremely efficient compared to the full range driver and will most likely require a larger baffle and/or a lower crossover point to try and reinforce the driver's natural rolled off SPL response. An equivalent high Qts driver will have a flatter low frequency response and will combine with the baffle response to yield a SPL response curve extending lower in frequency. My recommendation is to use woofer drivers that are at least 6 to 10 dB more efficient than the rest of the speaker system and having Qts values between 1.0 and 1.2.

Finally, reviewing the Lowther OB speaker system documented on my site reinforces some of the observations made in the preceding paragraphs. The Lowther OB speakers are a great sounding system but they are HUGE. The front baffle with wings extended measures 40" tall by 60" wide. It requires two Eminence Alpha 15A woofers and still needs bass boost from the active crossover. The baffle size, the number of woofers, and the bass boost were all driven by the approximately 98 dB/W/m of the Lowther PM2A full range driver. The minute I selected the Lowther drivers, I had backed myself into a huge speaker system with multiple woofers and an active crossover. A great sounding OB system but I learned about OB design trade-offs the hard way by constructing a brute force design. I am going to be smarter with the next OB design that I design and build.

References :

1) Linkwitz Lab (http://www.linkwitzlab.com)

2) Music and Design (no longer available)

3) Nomad Audio (no longer available)

4) GR Research (http://www.gr-research.com/)

5) Jamo Speakers (no longer available)

6) Hawthorne Audio (no longer available)

7) The EDGE (https://www.tolvan.com/index.php?page=/edge/edge.php) or even better BASTA by Tolvan Data (https://www.tolvan.com/index.php?page=/basta/basta.php) for the entire OB system.