By Martin J. King, 2/24/04 (revised 7/23/05)

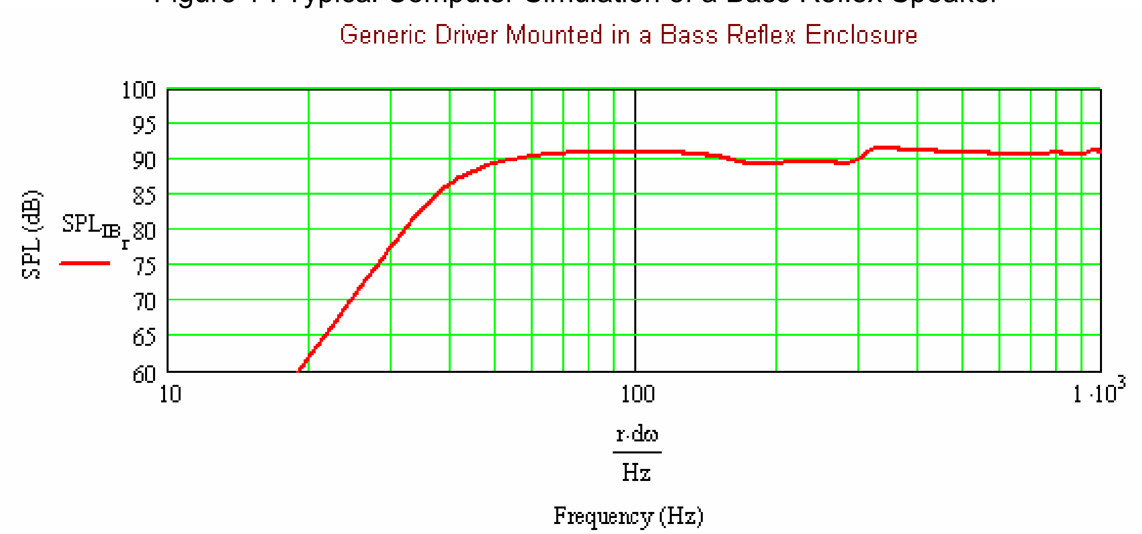
Introduction :

Over the past few years, I have become very aware of the baffle step response phenomenon associated with drivers mounted in rectangular shaped baffles. My first quarter wavelength designs suffered from a relatively depressed bass response and a dominating midrange and high end response. Shortly after completing my ML TQWT speaker article, I started to get private e-mails pointing out the possibility of a baffle step diffraction problem inherent in the design. I received several recommendations for changing the shape and size of the front baffle to push the frequency at which the sound field transitions from radiating into 4π space to radiating into 2π space lower in the frequency range. The method that I have been using to solve the baffle step response problem is the addition of a passive correction filter between the amp and the speaker. The intent of this short document is to describe baffle step response and present the equations required to size an appropriate passive correction filter.

Simulation Results :

When using most simple speaker design programs, one of the fundamental assumptions is that the speaker is radiating into 2π space. Figure 1 shows a typical plotted response, calculated using one of my MathCad worksheets, for a driver mounted in a bass reflex enclosure. Most other programs available on the Internet would yield a similar result.

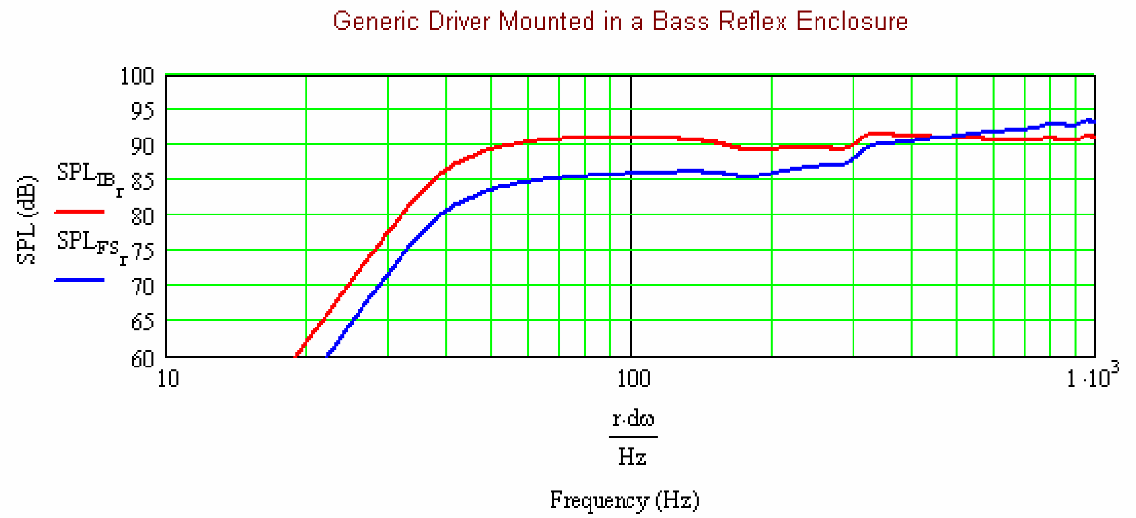
Figure 1 : Typical Computer Simulation of a Bass Reflex Speaker



The predicted SPL response is fairly flat and approximately 90 dB/watt/m at frequencies above 50 Hz. An inexperienced DIY speaker builder might mistakenly assume that if the enclosure is built per the program's modeled dimensions, that the SPL response will be very good. The only way that this simulation would be accurate is if the front baffle of the speaker enclosure were extremely wide and tall, in essence an infinite baffle, so the sound radiates only in front of the speaker enclosure. The subscript IB is used to denote the SPL produced by a speaker mounted in an infinite baffle radiating into 2π space.

The other extreme for simulating speaker performance assumes that the speaker enclosure is suspended and radiating into 4π space or free space. Free space implies that no reflective surfaces such as a wall, a floor, or a ceiling are close enough to influence the SPL response. At low frequencies the sound radiates equally in front and behind the speaker enclosure. The blue curve in Figure 2 depicts the SPL response, again calculated using one of my MathCad worksheets, of the same bass reflex enclosure design suspended in free space. For reference, the infinite baffle case, from Figure 1, is still shown as the red curve. The subscript FS is used to denote the SPL produced by a speaker radiating into free space.

Figure 2 : Computer Simulation of a Bass Reflex Speaker Radiating into Free Space



In Figure 2, the difference between the SPL curves is easily seen at low frequencies. There is a 6 dB SPL loss below 100 Hz for the speaker radiating into free space compared to the speaker mounted in an infinite baffle. The speaker radiating into free space has an unbalanced SPL response. The bass frequencies arrive at the listening position with half the volume level compared to the midrange and high frequencies. Words typically used to describe the sound of this type of speaker response are shouty, harsh, and fatiguing. At first a listener might be fooled into thinking that this speaker response is extremely detailed and revealing. It can be an alluring sound for a while, but usually after extended listening it becomes difficult to take. I can speak from personal experience.

Looking again at Figure 2, it is also apparent that as frequency increases from 100 Hz to 500 Hz the responses of the two simulations converge. A speaker radiating into 2π space or 4π space produces essentially the same volume of midrange output at the listening position. As frequency increases, the wavelength of sound decreases until eventually the size of the front baffle is big enough to be considered an infinite baffle. This transition from radiating into 4π space to radiating into 2π space, and the theoretical 6 dB gain in SPL output at the listening position, is referred to as the baffle step response phenomenon. All practical speaker designs have this problem over some frequency range.

For a speaker system radiating into free space, the SPL of the midrange frequencies compared to the SPL of the low bass frequencies can in theory present a 6 dB SPL mismatch at the listening position. However, in the home environment the reality falls someplace between an infinite baffle and a free space SPL response. The theoretical 6 dB SPL mismatch is really more like 3 to 4 dB once the room's reinforcement of the bass frequencies through reflections from the floor, the walls, and the ceiling are taken into account.

Method of Calculation :

From a given driver's Thiele / Small parameters, the SPL/watt/m can be determined. For example, a typical 8 inch diameter mid-bass might be listed by the manufacturer as being 90 dB efficient. Manufacturers typically measure their driver's response in 2π space using a very large baffle. If the same driver were placed in a typical rectangular enclosure and mounted in free space, the measured efficiency for the driver below the baffle step transition would be 84 dB (90 dB – 6 dB). The efficiency would then increase to 90 dB as the baffle step phenomenon comes into play for the midrange and high frequencies. The frequency midpoint of this transition from 4π space to 2π space can be estimated using the following relationship.

$$f_3 = 4560 / W_B$$

where

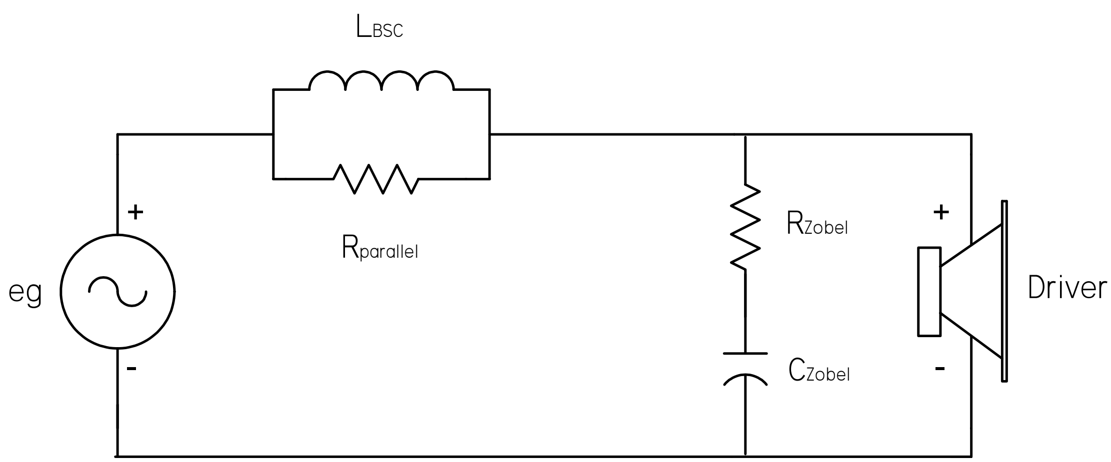
W_B = width of the baffle in inches

Correcting for the baffle step loss at low frequencies can be handled in several ways. One solution would be to extend the baffle width W_B to a very large value pushing the transition frequency below the systems operating range. This would lead to an extremely large baffle with no loss in driver efficiency. A second method would be applied in a two way design by placing the crossover point in the baffle step transition region and padding down the SPL output from the midrange driver and/or the tweeter driver. A third method is to apply a passive filter between the amplifier and the driver as shown by the schematic in Figure 3 at the top of the following page. I have used the third method in all of my full range speaker designs and found it to be a very simple, elegant, and powerful tool for rebalancing the SPL response across the entire frequency range.

There are different ways to design the filter shown in Figure 3. In the past, I used the finished speaker's measured impedance and SPL response as input into a MathCad worksheet for simulating the impact of the circuit and iterating to find an initial filter design. Then after the filter is constructed and installed, I fine tune the values by listening to the speaker located in my room. Listening is always the final proof test.

But most DIY speaker builders do not have the measurement tools required to design the baffle step correction circuit this way. Recently, I put together a simple calculation to be used as a sanity check on my MathCad simulations. It also occurred to me that this simple calculation method might be helpful for others looking to size baffle step correction circuits. Based on the final listening results from recently completed speakers, I have found these sizing calculations to be fairly accurate and require minimal component adjustments once the circuit is constructed and installed.

Figure 3 : Schematic of a Baffle Step Correction Circuit



There are two parts to the circuit schematic shown above. First, there is a Zobel correction circuit placed across the driver's input terminals to flatten out any rising impedance due to the voice coil inductance. Generally accepted equations for sizing the Zobel circuit components are shown below.

$R_{Zobel} = 1.25 \times R_e$ ohms

$C_{Zobel} = L_{vc} / (1.25 \times R_e)^2$ farads

where

R_e = driver's DC resistance in ohms

L_{vc} = driver's voice coil impedance in henries

The second part is the baffle step correction circuit consisting of the components denoted by L_{BSC} and $R_{parallel}$ in the schematic shown in Figure 3. To calculate the values of these two components, the following equations are provided.

$f_3 = 4560 / W_B$ Hz

$R_{parallel} = R_e \times (10^{dB/20} - 1)$ ohms

$L_{BSC} = R_{parallel} / (2 \times \pi \times f_3)$ henries

where

W_B = width of the baffle in inches

R_e = driver's DC resistance in ohms

π = 3.141592……

dB = amount of attenuation required

The value calculated for $R_{parallel}$ is a function of the amount of baffle step attenuation desired in dB. The formula for the inductor has changed from the one given in the original version of this document. Seth Murray, of Arpeggio Music in McMinnville Oregon, pointed out that $R_{parallel}$ and L_{BSC} have to be related to keep the midpoint frequency constant. If $R_{parallel}$ is adjusted to provide a different amount of baffle step correction the value of $L_{\mathbf{BSC}}$ must also change to maintain the same frequency midpoint. In the numerator of the equation for L_{BSC}, the resistance used is now $R_{parallal}$ instead of R_e as was shown in the original article. Using these relationships, a baffle step correction circuit is sized for the speaker system shown in Figures 1 and 2.

Sample Calculations :

Given the following driver and enclosure parameters :

R_e = 8 ohms

L_{vc} = 0.4 mH

W_B = 11 inches

Calculate the Zobel Circuit Elements :

R_{Zobel} = 1.25 x 8 = 10 ohms

C_{Zobel} = 0.0004 / (1.25 x 8)^2 = 4 uF

Calculate the Baffle Step Correction Circuit Elements :

f_3 = 4560 / 11 = 415 Hz

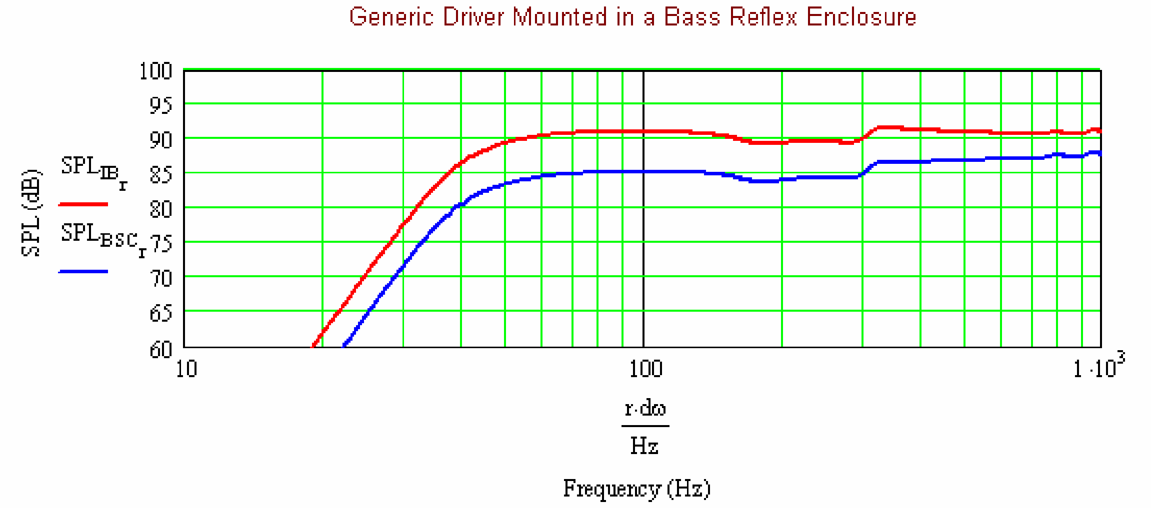
dB = 6 db = theoretical value for free space

$R_{parallel}$ = 8 x (10$^{6/20}$ – 1) = 8 ohms

L_{BSC} = 8 / (2 x π x 415) = 3.0 mH

Inserting this circuit in the MathCad simulation model, used to calculate the SPL responses shown in Figures 1 and 2, produces the response shown in Figure 4. Again the red curve is the original infinite baffle response and the blue curve is the free space response with the baffle step correction circuit installed. The curves have very similar shapes and both represent a balanced SPL response. The big difference is the loss of efficiency that occurs when the baffle step correction circuit is added to the speaker system; the blue curve is approximately 6 dB below the original red curve over the entire frequency range.

Figure 4 : Computer Simulation of a Bass Reflex Speaker Radiating into Free Space with a BSC Circuit



As stated earlier, in the home environment interaction with the room boundaries produces a SPL response between an infinite baffle response and a free space response. Looking at Figure 2, the in room SPL response would lie between the red and blue curves. Therefore the amount of required baffle step correction to yield a balanced SPL response would be less then the theoretical 6 dB value. Typically the required baffle step correction is between 2 and 4 dB and is strongly dependent on the room and the placement of the speakers in the room.

The same driver / enclosure simulation is used to size a variety of baffle step correction circuits, producing different amounts of dB correction, and the results are shown in Table 1.

Table 1 : Baffle Step Correction Circuit Components

W_B =	11	inches
f_3 =	415	Hz
R_e =	8	ohms

Correction	$R_{parallel}$	L_{BSC}
1	0.98	0.37
2	2.07	0.80
3	3.30	1.27
4	4.68	1.80
5	6.23	2.39
6	7.96	3.06
[dB]	[ohms]	[mH]

For this speaker, I would probably start with a L_{BSC} of approximately 1.5 mH and $R_{parallel}$ between 3 and 5 ohms. The final values for the circuit would be tweaked using listening tests. My guess is that less than a +/-1 ohm change in $R_{parallel}$ would required to achieve an optimum balanced SPL response. I would probably not change L_{BSC}.

Final Tweaking :

Using calculated values of circuit components, a filter can be constructed and installed between the amp and the driver as shown in the schematic. Now you need to listen and tweak until it is just right for your room, system, and personal taste. I usually perform the following steps to arrive at the final configuration.

1. Adjust the value of $R_{parallel}$
   a. If the bass is still too weak, then the amount of attenuation is too little. The value of $R_{parallel}$ should be increased until the bass seems to be balanced with the rest of the SPL spectrum.
   b. If the speaker sounds dull and lifeless, the value of $R_{paralllel}$ is too high. Reduce the value of $R_{parallel}$ to bring life back into the music.
   c. Continue adjusting $R_{parallel}$ until the speakers sound right to your ears. It is probably best to use acoustic music as a reference during this adjustment period.
   d. To remove the effect of the baffle step correction circuit completely, substitute a piece of speaker wire for $R_{parallel}$.
2. Adjust the value of L_{BSC}
   a. Depending on the final value of $R_{parallel}$, the original calculated value of L_{BSC} might need to be changed slightly. This sets the frequency range over which the baffle step filter attenuates the midrange and high frequencies. If the mid bass sounds depressed, then a lower value of L_{BSC} should be used. I typically perform this adjustment last once I am satisfied with the balance, between the very low bass and the midrange, I have achieved with the resistor.
   b. Decreasing the value of $L_{\mathbf{BSC}}$ will tend to warm the sound of the speaker if the previous value produced a depressed mid bass response.
   c. Always round down to the next available inductor size, having too low of an inductor value is a lot less problematic then having too large of an inductor value.
3. Final location of the circuit
   a. I usually spend many hours, over several days if not weeks, swapping resistor and inductor values until I am satisfied with the results.
   b. It is a real advantage to mount the circuit temporarily outside the enclosure during this time period.
   c. When the final version is ready, the circuit can be mounted inside the enclosure and soldered into place in the positive internal speaker lead.

Conclusion :

The preceding calculations and tweaking suggestions are intended to get you started down the path to an optimized baffle step correction circuit. There is no single answer for every speaker system and installation, be prepared to tweak until you are completely satisfied. You are the final judge and the only person that needs to be comfortable with the results.