You Can DIY!

The DSP Assisted Reflex System

Squeeze More Bass from Every Reflex Design

By
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(United States)

We all know reflex systems are more efficient and offer deeper bass than sealed systems. However, the vast majority still fall short of their potential by 6 to 12 dB or more. Worse yet, often people don't realize how vulnerable drivers are to damage. Many abuse woofers without knowing it. Few realize how much more sound output is possible from a DSP Assisted Reflex design.

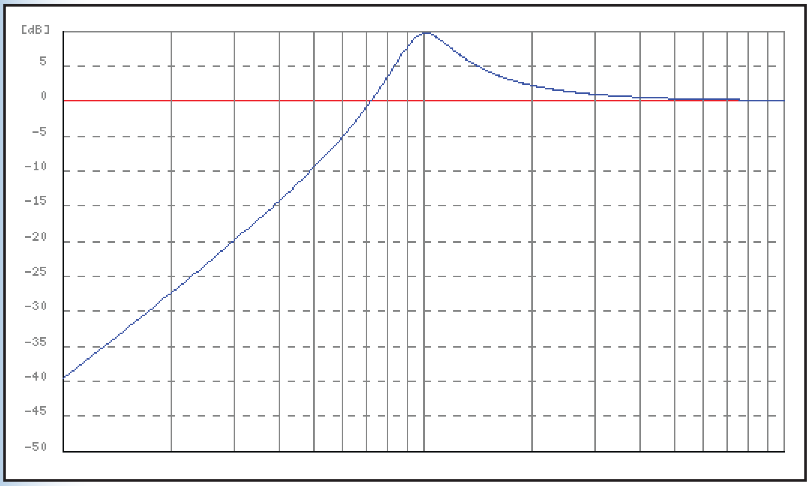

Figure 1: Gain function of a port or passive radiator. If you start with an ideal woofer (infinite bandwidth, acceleration constant with frequency) and put it in a ported box, the port amplifies the woofer's displacement by about 10 dB at f_b. Below about 0.7 f_b, the port cancels more than it reinforces output.

The Yin and the Yang of Vented Systems

The Yin: At the tuning frequency ("fb"), the port or passive radiator generates 70-80% of the air movement. At frequencies near f_b, cone excursion shrinks to a minimum. The box/port combination presents a stiff load to the driver. Thus, the driver has great leverage. Air displacement from the port approaches a maximum. In this band of frequencies, very high output is possible. Since the port output can easily exceed driver output by 3× (10 dB), a small driver can displace lots of air (see **Figure 1**).

The Yang: The full potential of a vented design is rarely realized. Most ports are too small and create air noise and losses. The proliferation of high X_{max} drivers makes this worse. Low-cost, high-power digital amplifiers make it even worse. The popularity of compact, low-efficiency systems makes it worse again, as I shall explain.

Solutions are neither difficult nor expensive. A revolution in vented enclosure design is now upon us. This article describes an easy DSP method that effectively doubles or triples real-world output.

It is well known that below resonance, a ported box ceases to resist the woofer's movement, unloading the cone and allowing out-of-control excursions. Everybody's heard "You should use a subsonic filter with vented speakers." I don't

Table 1: These are the parameters for the SB Acoustics SB15NAC30-8 6″ woofer.

Parameters	Results
F_s	35.50 Hz
V_{as}	17.70 ltr
Q_{ts}	0.37
Q_{es}	0.39
Q_{ms}	6
BL	5.9 Tm
Sd	82 cm^2
C_{ms}	1.86 mm/N
R_e	5.7 Ω
P_{max}	50 W
X_{max}	5 mm
SPL	86.4 dB 2.83 V/1 m

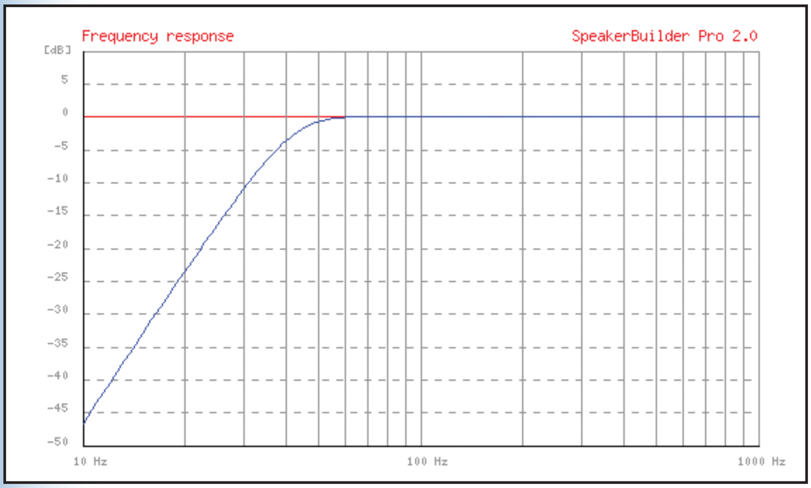

Figure 2: Frequency response of SB15NAC30-8 in a 12 ltr box tuned to 40 Hz

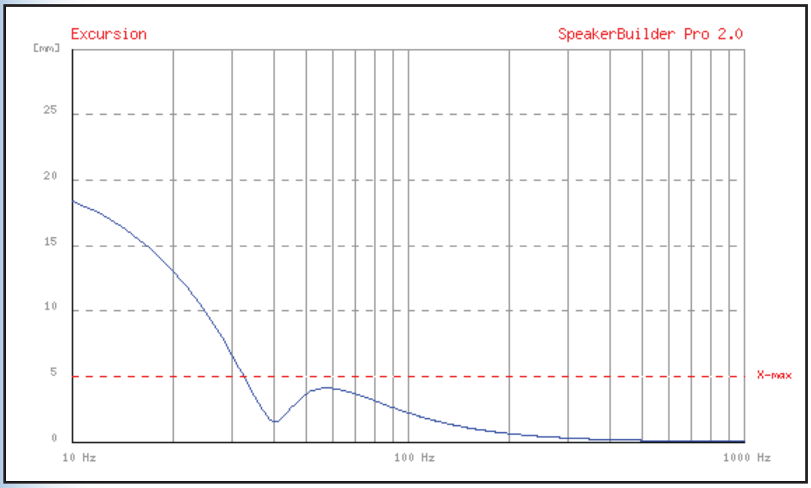

Figure 3: Excursion at 10 W input

know about you but I assumed we could ignore that when LPs gave way to CDs. And in my 30 years of designing speakers, I do not recall anyone fully articulating the severity of this problem. It's best illustrated with an actual example.

Consider the parameters of the 6″ SB Acoustics SB15NAC30-8 woofer (see **Table 1**). I put this driver in a reflex alignment, with a 12 ltr volume, f_b = 40 Hz (see **Figure 2**). X_{max} is 5 mm. Below 32 Hz, the system overloads at 10 W or less (see **Figure 3**).

Other results include:

- At f_b =40 Hz, the system's maximum output is 103 dB with 100 W input. The vent does nearly all the work.
- At 60 Hz (1.5f_b), the system's maximum output is 98 dB. Excursion exceeds X_{max} beyond 15 W input.
- At 20 Hz (0.5 f_b), the excursion hits its limit at 1.5 W input (!) and only produces 64 dB SPL.

Admittedly this is an unusually compliant woofer, but such problems plague all reflex systems. For a system with f_b near 40 Hz (a very common tuning range), bottoming or severe distortion with normal music is not only likely… it is a dead certainty.

Even at moderate volume levels, especially with house and electronic music, the woofer will be pressed to its limits by signals below 35 Hz. It will fall short of its sound pressure level (SPL) potential by 6 to 10 dB in its ideal band, 35 to 50 Hz.

Reflex boxes have a reputation for being boomy, muddy, or sluggish. I contend this is not because the reflex principle is inherently sloppy, slow, or inaccurate, but because of its acute below-resonance vulnerabilities. Problems come from the distortion and stresses caused by ignoring these issues.

Does Real Music Overload Normal Reflex Boxes?

The RS-426A specification prescribes band-shaped pink noise for power handling tests. It was created in the predigital era. Today, low-frequency digital content is even stronger. There is always a probability of overloading woofers below f_b. This is why it is normal for bass reflex systems to be in a state of overload.

A 30 Hz bass drum beat in a ported system tuned to 40 Hz emits a fatty blast of distortion with every thump, generating 60 Hz and 90 Hz harmonics and precious little fundamental (see **Figure 5**). One small consolation is that the human ear does register harmonics as evidence of the fundamental. Neither listeners nor designers know this problem can be solved quite easily (see **Figure 6**).

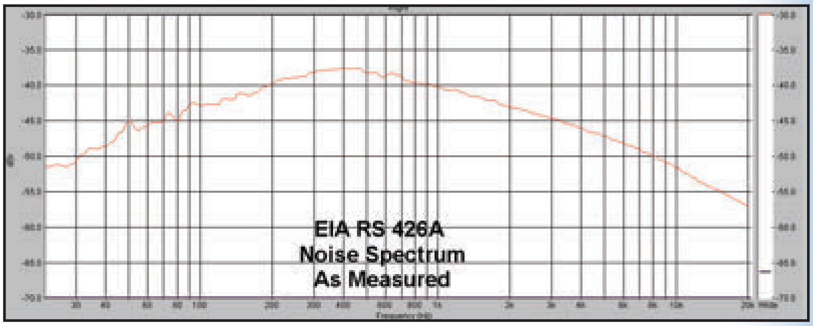

Figure 4: The RS-426A power test spectrum for speakers suggests that signal demand at 25 Hz is likely to be only 6 dB less strong than at 50 Hz, guaranteeing woofer overload in reflex systems. (Image courtesy of www.audioholics.com)

Port Problem

Small ports have whistling, turbulence and air noise. This causes compression and distortion at high volume levels. Large diameter ports don't make noise, but port length grows exponentially with diameter. A 5 cm diameter port that needs to be 10 cm long for 40 Hz tuning must grow to 40 cm long at 10 cm diameter.

Length and volume of the port can quickly outgrow the enclosure itself, especially if it's tuned to very low frequencies and/or the box is small. The availability of low-cost DSPs make low tunings especially attractive, so this is a common scenario. A passive radiator solves this problem by providing a large surface area and the ability to tune the system by adding weight to the cone.

Passive Radiator Problem

Care must also be taken that your passive radiator is large enough. Since it has to be able to move at least three times as much air as the driver at f_b, its volume displacement must be chosen accordingly. If the woofer has 5 mm X_{max} and the passive radiator has the same diameter as the woofer, the passive radiator needs at least 15 mm of cone travel each way. This will likely require a much better-than-average passive radiator. One system I designed using an 8" woofer with 12 mm X_{max} required a 12" "conventional" passive radiator to keep up.

If your passive radiator is up to the task, you will find even ordinary woofers are capable of surprising power across the octave between 0.85 f_b and 1.7 f_b (¼ octave below and ¾ octave above f_b). At the tuning frequency, the passive radiator adds about 10 dB to the woofer's maximum output!

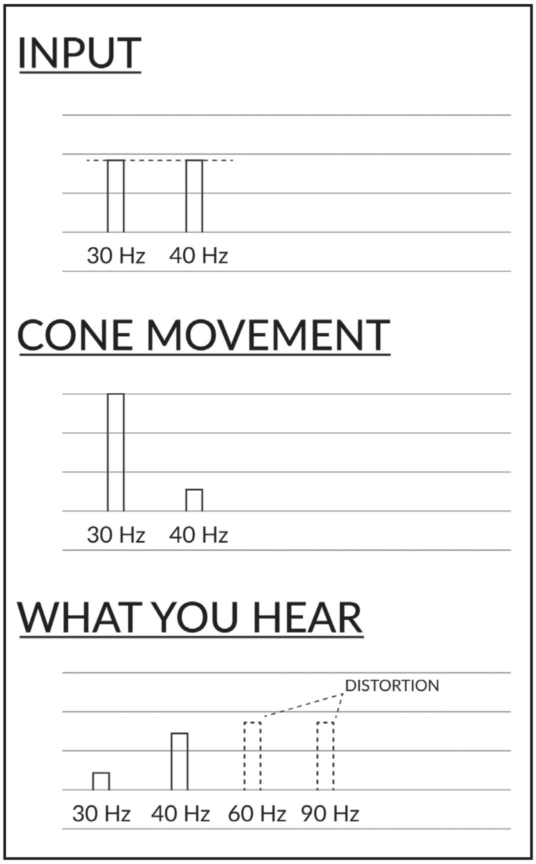

Figure 5: The behavior of a normal ported box without filtering is (f_b = 40 Hz). If you feed equal signals of 30 Hz and 40 Hz into a ported box with f_b = 40, the 40 Hz signal gets huge leverage from the port. But the 30 Hz signal makes the cone flap uncontrollably, producing little 30 Hz output and lots of distortion at 60 Hz and 90 Hz.

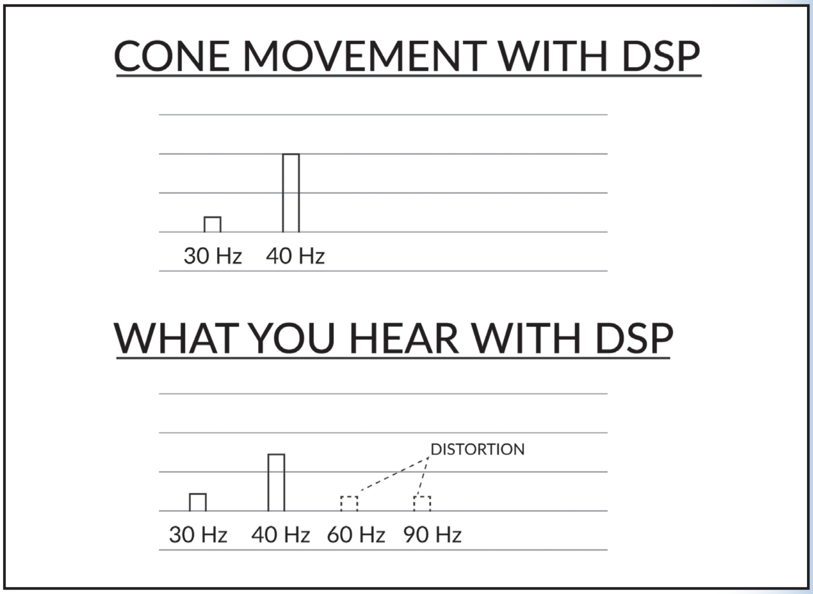

Figure 6: Cone movement after DSP is applied shows precision DSP Assisted Reflex drastically reduces useless cone movement and distortion, freeing cone travel for jobs the system is ideally suited.

The 80/20 Passive Radiator Alignment

The 80/20 principle is well known in business and manufacturing. Economist Vilfredo Pareto discovered a century ago that 20% of people owned 80% of the wealth, and 80% of the people owned the other 20% of the wealth. This was true across most countries, regardless of political structure.

80/20 is a natural inequality of cause and effect across hundreds of disciplines, where inputs and outputs are seldom equal. 20% of roads carry 80% of traffic; 20% of defects trigger 80% of product returns; 20% of stars have 80% of the planets.

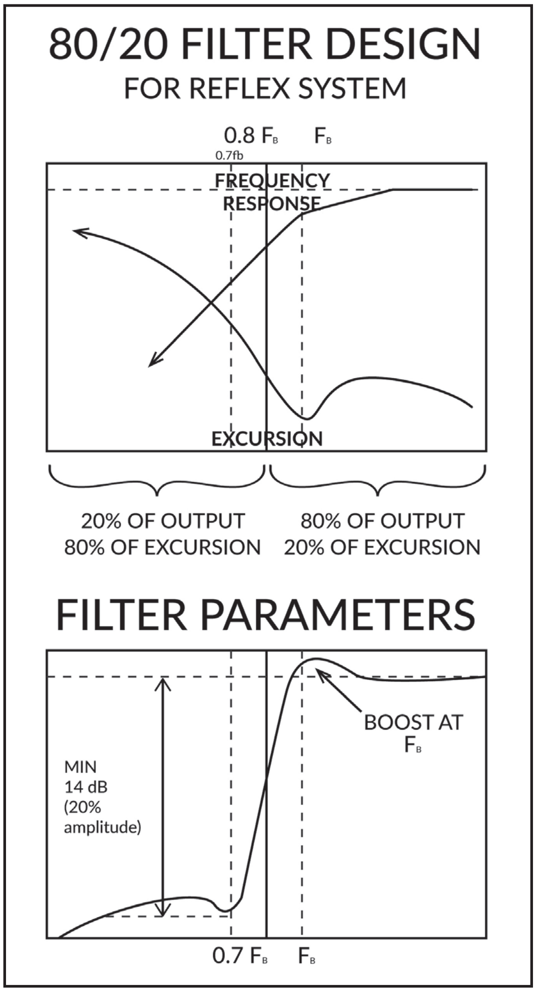

Figure 7: If the system is tuned low enough, most music will (hopefully) not overdrive the woofer below resonance.

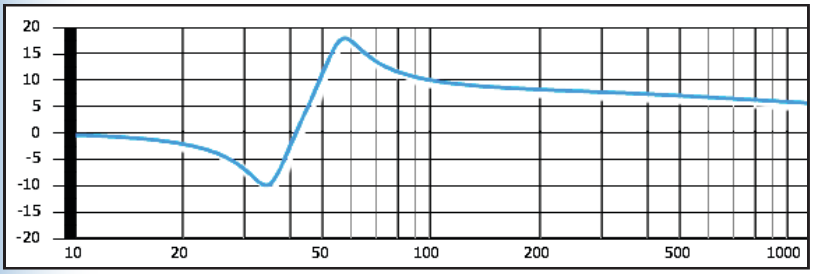

Figure 8: miniDSP has a high-pass shelf function with a high Q provides steep stopband protection while minimizing group delay.

80/20 analysis almost always reveals an area where 80% of energy is only achieving 20% of results. Knowledge of 80/20 yields opportunities to eliminate waste and accomplish more with less.

80/20 also applies to bass reflex behavior. At the tuning frequency, the speaker moves 20% of the air and the passive radiator moves 80%. The f_b frequency is its peak leverage point. As **Figure 2** and **Figure 3** show, at f_b you get a 4:1 "return on investment" for cone displacement.

A half octave lower, the situation reverses completely. If f_b is 40 Hz and if you simultaneously feed a 5 V 40 Hz signal and a 5 V 28 Hz signal, the 40 Hz signal will displace the cone 1 mm and the 28 Hz signal will displace it 4 mm. However the sound pressure (in Pascals) at 40 Hz will exceed the pressure at 28 Hz by 4:1.

So at 40 Hz, your "Excursion Return On Investment" is 4:1. At 28 Hz, "Excursion Return On Investment" is 1:4. Together, the two signals consume all of the driver's 5 mm X_{max}. The maximum SPL at 40 Hz then is only 88 dB.

80/20 passive radiator alignment says: Add a high-pass filter that reduces the 28 Hz voltage (and excursion) by 80% or 14 dB (see **Figure 7**). This frees up 3.2 mm more cone travel. Available excursion rises from 1 mm to 4.2 mm. When you grant the extra headroom to the 40 Hz signal, the increase is 12.5 dB for a maximum output of 100.5 dB.

If you reduce the 28 Hz out-of-band signal by 100% instead of 80%, it will buy you a 14 dB improvement instead of 12.5 dB. The promise of 6 to 12 dB at the beginning of this article is no exaggeration.

If the system is tuned low enough, most music will (hopefully) not overdrive the woofer below resonance. However, few systems are tuned below 25 Hz. Tunings between 35 and 100 Hz are typical, especially in computer and TV speakers. Since music almost inevitably contains significant below-f_b content, half to three-fourths of the driver's excursion abilities, which did not come cheaply, are wasted making the cone flap uselessly.

Below resonance, the reflex system is like a car engine revving at 6,000 RPM with the transmission in neutral. Little of the cone's travel gets spent where it really counts. In the real world, this costs you at least 6 dB of useful bass output, and as much as 14 dB.

If you study the woofer's displacement curve closely, you see that immediately below f_b, excursion skyrockets. It doesn't start to level off until around 0.7 f_b (1/2 octave below). So, you must reduce the 28 Hz signal to less than 20% of its original level, or 14 dB. You must do this between f_b and 0.7 f_b (0.5 octave). This actually requires a filter slope of

28 dB per octave. “That’s easy enough,” you might say. “I just get a 30 dB per octave high-pass filter and I’m good to go.”

80/20 High-Pass Filter

A high-pass filter is easy enough to implement. But several issues deserve close attention:

- A generic 20 Hz high-pass filter is far from optimum. You must match the filter to the specific system f_b. One size never fits all.
- The filter must apply at least 14 dB of reduction (80%) at 0.7 f_b to remedy the problem. To optimize the system to within 1.5 dB of its maximum output potential, the minimum filter slope between 0.7 f_b and f_b must be 28 dB per octave. A standard 18 dB/octave filter is insufficient.
- Traditional 24, 36, and 48 dB per octave filters introduce large group delays, which are plainly audible. More about this in a minute.

Recover Lost Bass and Dynamic Range

If you apply a “brick wall” filter at approximately 0.85 f_b and if your port or passive radiator has enough mojo, you’ll find: The system plays a lot louder and cleaner than it ever did before. The difference is startling. Try it.

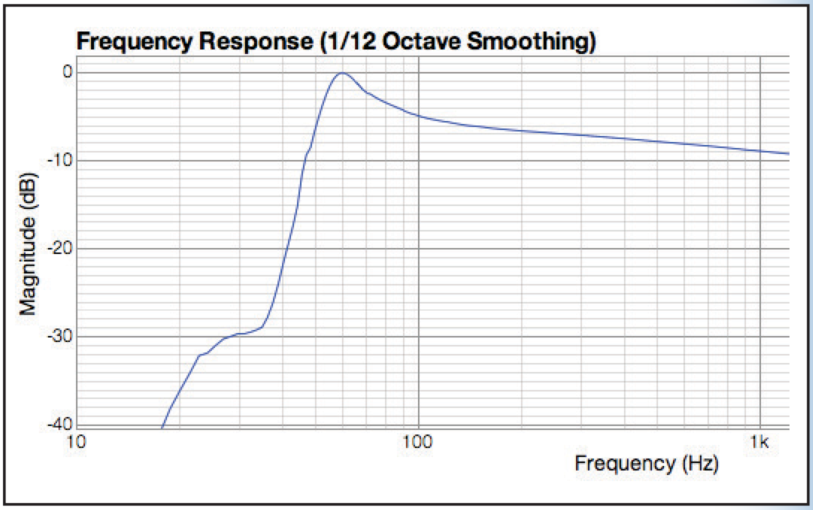

Figure 9: The 80/20 passive radiator EQ for a 3” full-range speaker is achieved by adding a 6 dB/octave high-pass filter to miniDSP’s high-Q shelf function. The peak at 56 Hz matches the f_b of 56 Hz. The boost corrects the system’s natural rolloff between 100 Hz and 50 Hz, and equalizes the system flat to 50 Hz. With a passive radiator and DSP assist, this 3.5” driver produces more bass from a 1-ltr box than you would normally consider possible.

Do the following experiment with any ported speaker on hand: Hook up a sine wave generator, determine the tuning frequency (by checking where

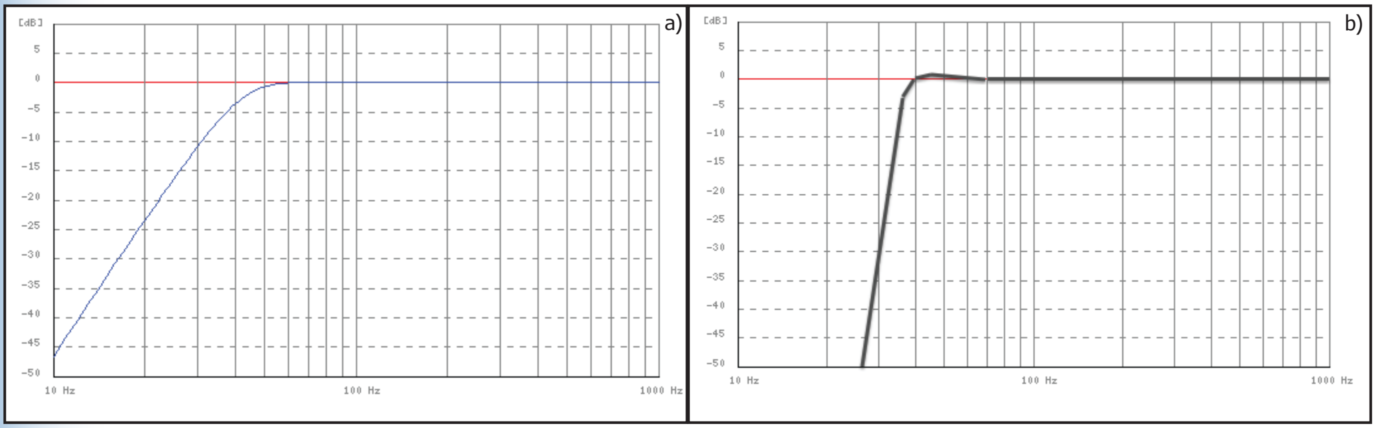

Figure 10: The speaker is shown at 40 Hz maximum then goes flat (a), and with the filter there is a simple rolloff but not much change (b).

the woofer excursion is a minimum), and set a steep filter at 0.85 times that frequency.

Then play bass heavy music, pushing the system to its limits. Switch the filter in and out. The first thing you'll notice is, when the filter is switched in, the missing below-f_b content is barely noticeable. The speaker was never delivering those low frequencies to your ears in the first place.

The second thing you'll notice is much less excursion (about half) with much less distortion at high power. The advantages of a steep high-pass filter set to just the right frequency are impressive. At high volume levels, it's like getting a entire new set of speakers.

But there is still another problem… and another exciting opportunity we haven't explored yet. You can do much better than a traditional sixth- or eighth-order high-pass filter.

Time Delay of Steep Filters

Once I built an active system based on the Behringer DCX2496 crossover, which has continuously adjustable 6, 12, 18, 24 and 48 dB/octave digital filters. I initially loved the idea of steep filters, until listening showed me that steep filters sounded much worse.

I had always heard audiophiles talk about this (especially purists who insist on 6 dB per octave crossovers). I was dismissive, knowing all too well that real-world 6 dB slopes are outrageously difficult to pull off.

The surprise came playing Porcupine Tree's song "Fear of a Blank Planet." It is a superb recording. Gavin Harrison's bass drum is tuned to a very low frequency, so it's a great low-bass subwoofer test recording. Not only is the bass visceral, the drum also has a lot of "slap." Gavin's bass drum covers six or eight octaves of spectrum.

I found that with steep slopes, I could actually hear the low bass pulse arrive later—at a different "date"—than the slap of the bass drum.

The delay was plainly obvious. I looked at some filter charts and verified: a 24 dB per octave 20 Hz high-pass filter has an inherent delay of 27 ms at 20 Hz. A 48 dB per octave 20 Hz filter has an inherent delay of 56 ms.

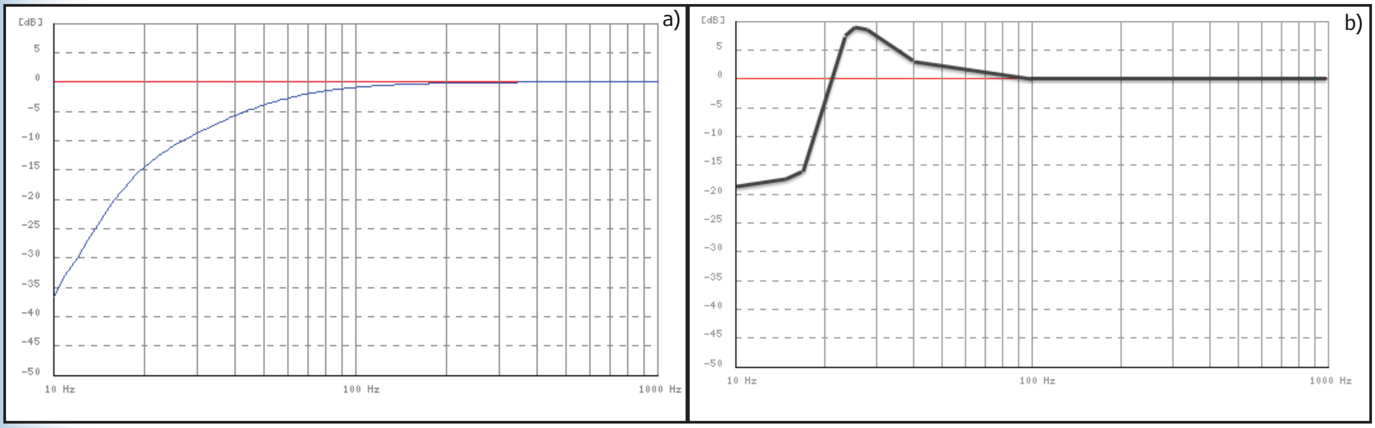

Figure 11: The speaker when tuned to 25 Hz (a), and the corresponding filter (b).

My friends, you can hear 27 ms. That's almost 1/30 of a second. On a metronome, that's the difference between a tight drummer and a sloppy one. Pundits, reductionists, and anti-subjective audiophiles argue that the human ear can't hear phase differences. If you think you can't hear phase shift, try the experiment yourself.

I also found I could hear a similar difference at the 300 Hz crossover. It was not as obvious, but was evident in the integrity of percussion like snare drums. Steep slopes make drums sound slightly disembodied.

So while I could solve reflex excursion problems with 36-plus dB crossovers, I was still looking for a better solution, one that didn't have long delays. I found one in an unexpected place!

Modern DSPs offer exciting solutions to these problems for little money. You can explore many possibilities with a passive radiator plus DSP alignment. If you're going to use electronic correction at all, you might as well apply creativity and use it to its full potential. DSP re-invents vented systems for the 21st century.

80/20 DSP for Passive Radiator Systems

miniDSP.com provides affordable DSP units that are programmable via USB cable from a Mac or PC. You can combine crossover slopes, time offsets, peak filters, and notch and shelf filters. A combination of high-pass filters and peak/notch filters could give any response curve I was likely to need.

Things got especially interesting when I began experimenting with miniDSP's shelf function. Its shelf filters have variable Q, and with a higher gains (8 to 15 dB) and higher Qs (2-5), I was able to achieve very interesting, very useful shelf functions that achieved the steep 30 dB slope I needed just below f_b (see **Figure 8**).

Note that instead of continuing to roll off, these filters level off. On the surface, this might appear to be a problem. But it's not. Because in all practicality, if your initial shelf is deep enough, you don't need much further rolloff at ever-lower frequencies. If the attenuation of the shelf is 15 to 25 dB, that's good enough. I add a 6 dB/octave high pass for good measure (see **Figure 9**).

Bose 901: A Classic EQ Assisted, Extended Reflex Alignment

The venerable Bose 901 is an actively assisted bass reflex system with an abnormally low tuning frequency. The 901 and its pro-sound cousin, the 802, both have a reputation for respectable bass, especially considering their sizes. The 901 embodies several of the key ideas in this article, and carries them to an extreme.

The 901's f_b is 40 Hz (see US Patent 4146745). Its active equalizer sharply cuts off response below 35 Hz. **Figure 1** shows the curve of the active EQ from the patent.

Rarely does one see a 4.5" woofer tuned as low as 40 Hz. If the 901 were an acoustic suspension system or if it didn't have custom EQ, results would be poor. But nine 4.5" woofers are equivalent to a single 13" woofer. And tightly integrated such as it is, the 901 achieved solid bass and become one of the great classic speakers in the history of the audio business.

The 901 illustrates the power of using EQ to take full advantage of the reflex system's 80/20 leverage. (In the 21st century, DSP is also a much better way to achieve this than analog EQ.)

The Bose 802 professional version illustrates a second principle, which we explore in the main article: The ability to trade bandwidth for output. The 802 ports are tuned to f_b = 55 Hz and the EQ boost is at 50 Hz not 35, with sharp cutoff below that frequency. This increases the maximum output of the speaker by 5.5 dB. In pro sound reinforcement, the extra 6 dB at 55 Hz is more useful than extending bass to 40 Hz.

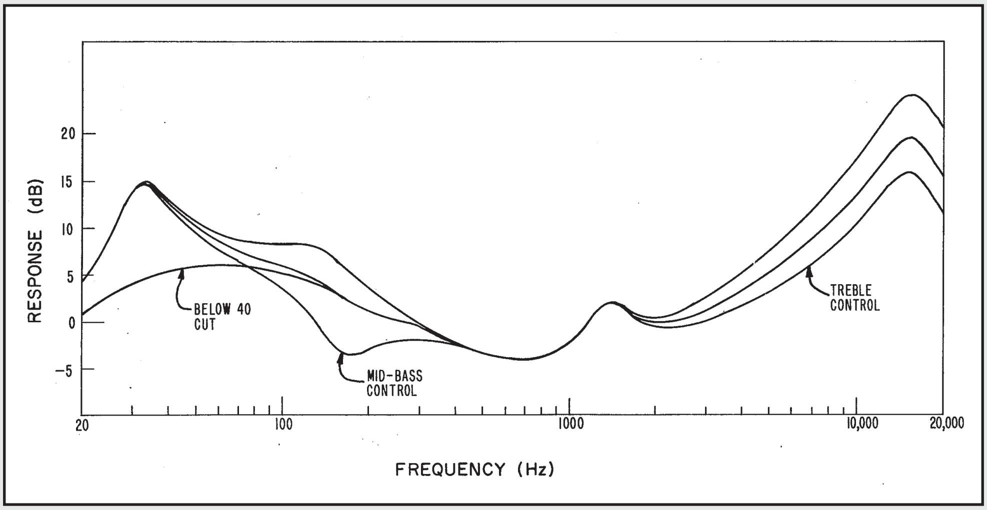

Figure 1: Here is the EQ for the Bose 901, an actively assisted, low-tuned reflex alignment. Notice the 15 dB boost at 35 Hz and sharp cutoff below.

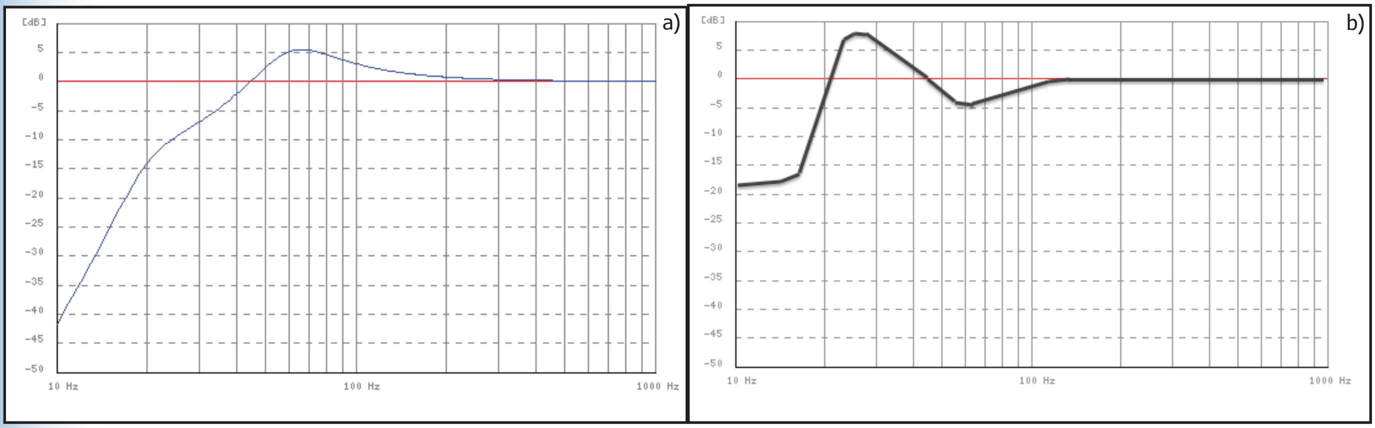

Figure 12: Here EQ is used to boost the response. Response of the speaker (a) and corresponding filter (b).

This has a hidden advantage: far less group delay than a traditional steep filter. I found if I combined a Q = 3, gain = 10 dB shelf filter with a simple 6 dB per octave high-pass filter, I got the well-behaved phase of a shallow filter with the protection of a steep one.

This configuration is formally known as an elliptic filter. An elliptic filter is one where, in order to achieve a very steep slope over a narrow range, you accept peaks and dips (ripple) in both the passband and the stopband. DSP crossovers are as superior to standard active crossovers as active crossovers were superior to passive crossovers.

Ripple Is Where the Magic Is

Since we have access to cheap DSPs, solved a major excursion and distortion problem, and can achieve 6 to 14 dB more output, it's also time for the fun part. DSP Assisted Reflex lets you shape bass extension to your heart's content. This gives you enormous flexibility in driver choice along with box size, extension, and dynamic range. You have options that would be unimaginable with purely passive systems.

For decades, systems have been designed around a standard family of alignments, most typically "maximally flat" Butterworth or QB3 ("quasi-Butterworth). Since reflex behavior is complex, it was necessary to restrict options to a handful of easily understood goals, especially before computers made it e-a-s-y to model any imaginable alignment.

When active EQ has DSP precision, your options expand exponentially. You now have three distinct options:

- Simply match a custom high-pass filter to a normal, maximally flat system for higher output (see **Figure 10**). This is the most straightforward but least interesting way you can configure a DSP Assisted Reflex. However, it fails to get the maximum output from the woofer with a given amount of X_{max}. The next two options have higher maximum output in the real world, as I shall explain.
- Tune the passive radiator to a much lower frequency, then boost the bass at f_b with DSP (see **Figure 11**). This extends bass well below what is normally considered possible in a small box. This is far more interesting than the first option. Cone excursion is normally the #1 limiting factor in bass output. Since the passive radiator amplifies cone excursion by 10 dB at f_b, boosting the range near f_b with EQ produces surprising results.
- Tune the passive radiator to a lower frequency and use EQ to boost response at f_b (for bass extension), plus compensate for a high Q woofer/undersized enclosure. The mid-bass notch relieves the amplifier of some power burden over a narrow band. It also permits drivers and alignments that would have never made any sense for a vented system before DSP (see **Figure 12**).

The second and third options generate higher maximum output with real music than the first option. Why? Because the DSP boost at f_b ensures that the woofer is driven to maximum excursion at frequencies near resonance. The port, in turn, triples the air displacement. In the first option, the woofer is seldom pushed to its limits near f_b and you'll rarely get the 10 dB additional output that a ported system is theoretically capable of.

WARNING: You need to exercise caution because it's easy to push the woofer past its thermal limits, even though it's well within its mechanical limits.

How Low Can You Go?

In theory, you can tune a passive radiator as low as you want. Practically, it's a question of how far you can stretch while still producing useful output. Sure, you could match a 3" woofer to a passive radiator tuned to 20 Hz. But who wants a subwoofer with a maximum SPL of 55 dB?

Engineering for flat response is no longer your initial goal, since you make corrections later with DSP. Even the size of your box is not based on what will get an ideal flat response anymore. Instead it is determined by the box size/efficiency compromise you choose. Likewise, when tuning the passive radiator, you have a range of choices. You tune the passive radiator based on how much output capability you desire at critical bass frequencies.

At f_b, the vent or passive radiator is responsible for at least two thirds of the output. This translates to 10 dB more output than the woofer can produce all by itself. The exact amount of passive radiator gain depends on how lossy the box and port are. Are there leaks in the box? Port turbulence? Does the passive suspension have resistance?

Your range of tuning choices is:

Photo 1: DSP makes it possible for a 3" full-range driver (Fountek FR89EX) and 5" passive radiator (rear mounted) to achieve 55 Hz to 20 kHz in a tiny 1-ltr box with surprisingly high output.

About the Author

Perry Marshall (www.perrymarshall.com) designed speakers for Ford, Acura, Honda, and Chrysler in the 1990s. He's author of the books *Industrial Ethernet*, *80/20 Sales & Marketing*, and *Evolution 2.0: Breaking the Deadlock Between Darwin and Design*. He has a BSEE from University of Nebraska. He's applied principles of communications and control systems to a range of fields, from audio and advertising to information technology and genetics.

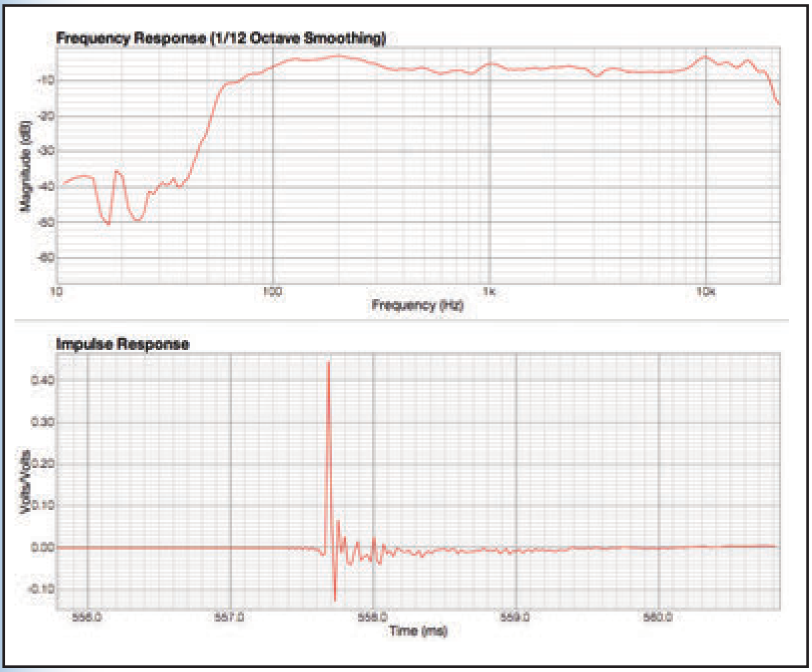

Figure 13: A pair of speakers generates more than 100 dB SPL at 55 Hz in a 12′ × 19′ room. The system has no crossover and, as you can see from the extraordinary clean impulse response, the phase accuracy is superior to 99% of all two- and three-way speakers.

10 dB SPL boost and no bass extension ↔ No SPL boost and ¾ octave bass extension

The maximum SPL of any specified amount of air movement falls 12 dB per octave with decreasing frequency. If your woofer can produce 100 dB at 40 Hz in a sealed box, when you can add a passive radiator tuned to 40 Hz, the maximum SPL at 40 Hz will be 110 dB. Place that same woofer in a sealed box and it will produce 88 dB at 20 Hz. Add a passive radiator tuned to 20 Hz and your system will produce 98 dB at 20 Hz.

Or if you tune the port to 24 Hz (¾ octave below 40), your system will produce 100 dB at 24 Hz. Of course, response and maximum output will drop like a rock below f_b.

Most designers will go for something right in the middle—almost half octave bass extension and 5 dB output boost. In this example, the happy medium is f_b = 31 Hz. At that frequency, the maximum output is 105 dB.

DSP makes it possible for a 3″ full-range driver (Fountek FR89EX) and 5″ passive radiator (rear mount) to achieve 55 Hz to 20 kHz in a tiny 1-ltr box (!) with surprisingly high output (see **Photo 1**). A pair of speakers generates more than 100 dB SPL at 55 Hz in a 12′ × 19′ room. The system has no crossover and as you can see from the extraordinary clean impulse response (see **Figure 13**). The phase accuracy is superior to 99% of all two- and three-way speakers.

DSP Assisted Reflex: The New Way to Design a Loudspeaker

For decades, we would design a vented box by entering the Thiele-Small (T-S) parameters of the driver into a box design software program, and choose a fixed alignment that suited our needs. Then, we would tweak the details and build the box. However, there is another solution.

The 80/20 DSP approach is:

1. Choose your box volume first, which determines neither bandwidth nor maximum output, but efficiency in the lowest octave. Bigger box = more SPL for less power. Even a small box can be tuned very low, if your budget and your woofer can handle the power.

2. Choose your tuning frequency f_b. This sets the band where your Passive Radiator is going to add 10 dB of "displacement gain." You can set that frequency high, favoring high output (as with the Bose 802) or tune it lower for deeper bass (as with the Bose 901). But there is a tradeoff:

- One octave bass extension ($f_{new} = 0.5f_{old}$) costs you 12 dB in maximum output
- Half octave bass extension ($f_{new} = 0.707f_{old}$) costs you 6 dB in maximum output
- Each 20% reduction in frequency (1/3 octave, i.e., 50 Hz to 40 Hz, or 40 Hz to 32 Hz) costs you 3 dB in maximum output.

3. Set your DSP EQ with maximum boost at f_b and at least 14 dB of low frequency protection at 0.707 f_b. Apply notch filters to solve other problems as necessary.

To harness the full strength of today's high X_{max} woofers, you must use a large diameter and a long port or a passive radiator that can handle three times the air displacement of your woofer! If you follow these rules, the 80/20 DSP Assisted Reflex will have up to 10 dB higher maximum output than a sealed system, and more output than old-school reflex designs, with almost no disadvantages.