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Five Speaker Myths Undone

By Mark Sanfilipo

The worldwide Internet is a critical tool in this information age. But it can also lead to widespread misconceptions, which this article attempts to clear up.

In my spare time I've been known to peruse various websites, newsgroups, and other online forums devoted to all things loudspeaker. Over the years I've learned quite a bit, gaining further insights into the art and science of speaker building from both luminary and amateur enthusiasts alike. And if you, like me, spend any time following the variegated tracery of threads which make up these various online resources, you'll also know the noise-to-useful-information ratio can be very large indeed.

I've often seen it happen that an idea or concept, lacking little or no technical merit or validity, is promulgated as truth. I've elevated to the rank of "myth" those seemingly inevitable items that pop up year after year. I've looked at some of my favorites under the objective light of hard science, and I'd like to share the outcome of my own investigation into these favorite myths of mine.

1. DAMPING FACTOR

Quite a large amount of online text has been devoted to this item in the forums I mentioned earlier. Reading the various discussions raging back and forth between contributors over the years, I get the general sense that most folks make too much of the amplifier's contribution to the total system damping factor—and its effect on system performance.

Damping factor (DF) is defined as the ratio of the load impedance (usually taken as 8Ω) to source impedance. It is a dimensionless figure of merit and therefore has no units ascribed to it. In practical terms, when applied to an amplifier, it indicates to what degree the amp can dissipate the energy generated by a driver's voice coil as the coil's post-impulse motion decays to zero: thus is the mechanical vibration electrically damped.

But focusing solely on DF as determined by an amplifier's output resistance (Rg) is simply too narrow in scope; its Rsource, the sum of Rg, cable resistance (Rcable), crossover network component resistance (Rcomponent), and Revc (voice coil resistance) determine the true DF as seen by the driver. In fact, focusing on Rg alone also ignores the single largest contributor to DF: the driver's voice coil.

To resolve a clearer picture of DF, I ran a series of simulations to determine to what degree various damping factor values as determined by Revc, Rg, Rcable, and Rcomponent affect system response performance at resonance frequency.

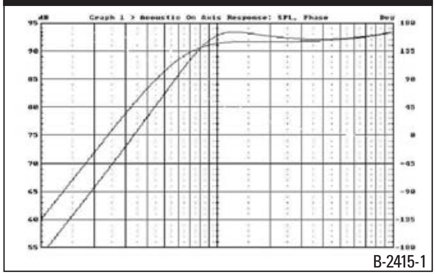
In the first simulation set, I used a test model representing a closed-box system, whose initial design was based upon DF = 8, Rsource = 0Ω, where:

Rsource = Rg + Rcable + Rcomponent (Ω)

and a Qtc = 1/v(2), (Butterworth B2 alignment) producing a maximally flat response, with zero peak at resonance.

Although DF is typically specified at a load impedance value of 8Ω, I used Revc = 6.2Ω, which was the Revc parameter value of the driver I modeled (KEF B139). If you're more comfortable thinking of DF in terms of the usual 8Ω load, convert the given 6.2Ω-based Rg figure by multiplying the given values by 1.2903. At any rate, in running the analysis, some interesting trends emerged from the data generated by the simulations (*Fig. 1*).

FIGURE 1: System response at DF = 1 and DF = ∞.



As I mentioned earlier, the Rg, or amplifier output resistance, in actual practice is only part of Rsource; all three components of Rsource, along with Revc, combine to affect DF. Of all resistance component values, however, Revc is typically by far the largest and therefore has the greatest effect on DF.

Rsource affects Qec, which in turn affects system QTC. Rewriting the well-known formula for calculating QTC from Qec and Qmc, but taking into account Rg, Revc, Rcable, and Rcomponent, gives:

$$Qec' = 2\pi * fc * Mmc * \frac{Revc + Rsource}{B^2 l^2}$$

where: Qec' = system Q at resonance (fc), due to electrical losses, including Rsource, dimensionless
fc = system resonance of totally enclosed box (TEB), Hz
Bl = force factor, magnetic flux density in voice coil gap * coil winding length, TM

Rsource = Rcable + Rcomponent + Rg (Ω)

Plug Qec′ into the well-known equation used to calculate Qtc.

$$Qtc' = \frac{Qec' * Qmc}{Qec' + Qmc}$$

where:
Qtc′ = total system Q at resonance (fc)

due to both mechanical and electrical losses, taking into account Rsource, dimensionless
Qmc = system Q at resonance (fc), due to mechanical losses, dimensionless

A cursory examination of these formulae shows that as Rg increases, so too does Qtc′, and with the increase in Qtc′ comes an increasing response peak at resonance. And, of course, adding the other two components that make up Rsource, Rcable, and Rcomponent produces even larger changes in Qec, Qtc, and system response at resonance (*Figs. 2–5*).

The question is, at what point does the effect of declining DF become audible? Looking at the first dataset, which I generated considering Rsource, it would appear that only in the very worst cases do these changes enter the realm of possibly audible. And setting the upper value limit of Rsource = Revc is certainly an extreme case (*Table 1*). Noting the position of Rsource in the Qec′ equation tells you that keeping it as low as possible is helpful, but only modestly so given that Revc, under typical circumstances, is much, much larger.

The key to understanding the true nature of DF is realizing that it's the *total resistance seen by the driver's motor coil* that counts and that Revc is—by far—the largest, single most important contributor to the total resistance value of the amp/cable/component/voice-coil circuit. Because the value of Rsource tends to be << Revc, Rsource doesn't much change the degree of damping the driver experiences at resonance owing to its own Revc. Why?

Damping is energy dissipation—here in the form of direct conversion of electrical power into heat, with the end result said energy is no longer stored in the system. Typically, 95%+ of the power supplied by the amplifier winds up as heat generated by the voice coil.

To get a clearer picture of where and to what degree dissipation occurs within the amp/cable/component/voice-coil circuit, I ran a simulation of a driver based on a circuit (*Fig. 6*), the schematic of which some of you may recognize in my earlier *Speaker Builder* article ("Pspice Probes a Loudspeaker's Evolution," 1/99, p. 26). In that article, I demonstrated how to produce an accurate model (with both temperature- and frequency-dependent components) of a raw driver using PSpice. I've added Rg, Rcable, and Rcomponent values, retaining the original model Revc value of 4.15Ω, found in that earlier article. I then probed for power dissipation at each of the four components to see how and where power was being dissipated. If you'd like to experiment with the model using your own circuit editor/analyzer,

FIGURE 2: Attenuation (dB) vs. damping factor.

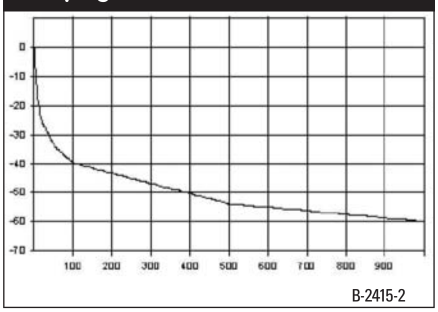


FIGURE 3: Resonance peak (dB) vs. damping factor

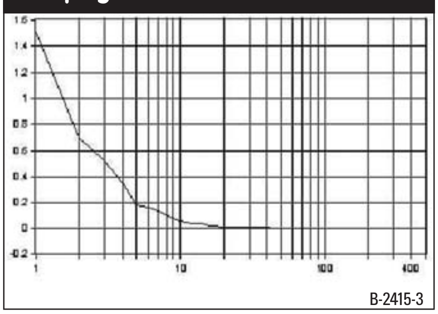


FIGURE 4: QTC vs. Rg (ohms).

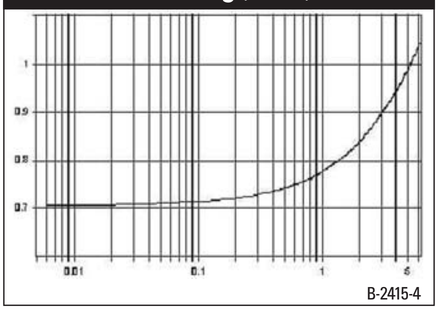


FIGURE 5: Q_{TC} vs. damping factor.

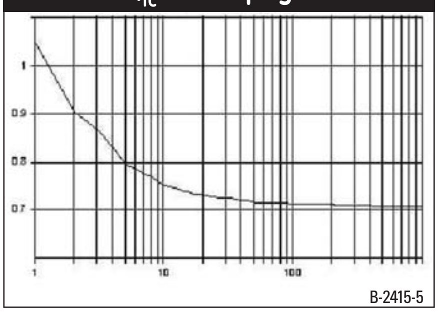


TABLE 1: DF, Rsource, and resulting variations in electrical attenuation, resonance peak, and Qtc'

DF	Elec. Attn. (dB)	Rsource (Ω)	Resonance Peak (dB)	Qtc'
∞	-20*Log(∞)	0.0000	0.00000	0.7071
1000.0	-60.000	0.0062	0.00000	0.7075
500.0	-53.970	0.0124	0.00000	0.7079
100.0	-40.000	0.0620	0.00060	0.7116
50.0	-33.979	0.1240	0.00270	0.7161
20.0	-26.020	0.3100	0.01580	0.7295
15.0	-23.520	0.4133	0.02717	0.7368
10.0	-20.000	0.6200	0.05676	0.7512
5.0	-13.979	1.2400	0.18422	0.7925
2.0	-6.020	3.1000	0.69477	0.9013
1.0	0.000	6.2000	1.50960	1.0447

FIGURE 7: SPICE net list for test circuit.

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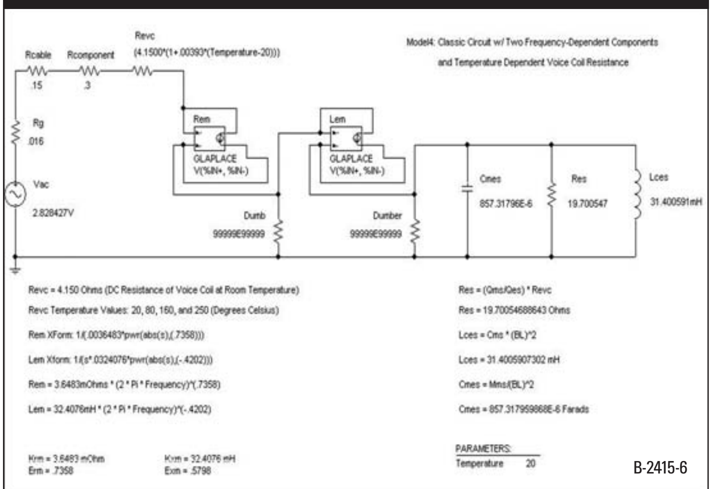
```
CIRCUIT DESCRIPTION ****
******************************
.PARAM          Temperature=20
** Analysis setup **
.ac DEC 101 10 40K
.STEP PARAM Temperature LIST
+ 20 80 160 250
** Schematics Netlist **
R_Dumb          0 $N_0001  99999E99999
R_Dumber        0 $N_0002  99999E99999
G_Lem           $N_0001 $N_0002 LAPLACE { V($N_0001, $N_0002) }
                { + 1/(s*.0324076*pwr(abs(s),(-.4202))) }
C_Cmes          0 $N_0002  857.31796E-6
R_Res           0 $N_0002  19.700547
L_Lces          $N_0002 0  31.400591mH
G_Rem           $N_0003 $N_0001 LAPLACE { V($N_0003, $N_0001) }
                { +  1/(.0036483*pwr(abs(s),(.7358))) }
V_Vac           $N_0004 0 DC 0V AC 2.828V
R_Rg            $N_0004 $N_0005  .016
R_Rcable        $N_0005 $N_0006  .15
R_Rcomponent    $N_0006 $N_0007  .3
R_Revc          $N_0007 $N_0003  {4.1500*(1+.00393*(Temperature-20))}
```

I've included the netlist generated by PSpice (*Fig. 7*).

Once I ran the simulations it was easy to see from the generated output graphs that, indeed, the majority of dissipation—and therefore damping—was taking place in the Revc component of the circuit, i.e., the driver's voice coil (*Fig. 8*). In the graph, the topmost trace is that of Revc, which clearly indicates that Revc is the point in the circuit where the most power is being dissipated.

Hence, it has the greatest degree of control in determining the DF of the circuit. By this point in the analysis it should be clear—when it comes to DF—that real control lies with the driver's voice-coil Revc and not with Rsource. Having said that, there is, however, good reason for keeping Rsource as low as possible. Looking at its effect on dB SPL loss, separate from DF, where:

FIGURE 6: Test circuit.



$$dBSplLoss = 20 * Log(\frac{Zevc}{Zevc + RSource})$$

Here, Zevc represents the frequency-dependent impedance of the driver's voice coil, in ohms. This equation illustrates that increasing Rsource results in greater dB SPL losses. Given this fact, best practices dictate keeping Rsource as low as possible.

From the preceding investigation I think it fair to draw the conclusion that amplifier DF has very, very little effect on the total circuit DF, and what little effect it does have occurs in only the very worst of cases.

2. MAGNETIC SHIELDING

Online threads typically start with someone bemoaning the fact that their latest design, now made reality, can't be placed next to their TV or CRT computer monitor without causing the display to become distorted. What to do?

Soon there follows lots of well-intentioned suggestions—frequently possessing scant traces of technical merit—to shield or enclose the monitor or loudspeaker with a variety of metals. To sort the rubbish from the useful suggestions, I ran a series of Finite Element Analysis (FEA) analyses, each modeling a different suggestion on how to conquer video display distortion. My analyses

TABLE 2: Metal Properties

	Resistivity (Ω -cm)	Density (gm -cc)	Mag. Susc. (cgs/g)	Temperature Coefficient	UNS ID Number	Notes
Silver (AG)	1.55e-006	10.491	2e-007	0.0038	-	Pure, NF
Copper (Cu)	1.70e-006	8.96	-8e-008	0.00382	-	Cold Drawn, Pure, NF
Copper (Cu)	1.71e-006	8.89-8.94	-1, 04 × 10-6 cm3/g	0.00382	C10100	OFC, NF
Gold (Au)	2.22e-006	19.32	-1.42e-007	0.0034	-	Noble Metal: does not react with air. Pure, NF
Aluminum (Al)	2.7e-006	2.6989	6e-007	0.0039	-	Pure, NF

NF = Non-ferromagnetic

will show, in the end, the old saw "an ounce of prevention is worth a pound of cure" definitely holds true where it comes to effectively corralling stray magnetic fields.

The first simulation is that of a magnet/steel structure with its magnetic field free to fill the air surrounding it (*Fig. 9*). The squiggly lines surrounding the structure are magnetic field lines, scaled in webers. Any electrons streaming through the magnetic field (such as those found in an energized cathode ray tube) will be pulled off course, resulting in all sorts of image distortions.

One solution, of course, is to keep that magnetic field from getting near the electron path. Moving the field source a sufficient distance from the CRT gun would clear things up, as the farther the distance from the source the lower the flux density, but that only addresses the symptoms, not the underlying pathology. As well, space constraints may make putting enough space between monitor and speaker impractical.

For my second simulation (*Fig. 10*), I modeled another common suggestion: place a shield between the loudspeaker and the CRT. In this case I placed a sheet of aluminum squarely in the path of the field and it did . . . just about nothing. Look at those lines—they're having a field day (pun intended)!

This looks like a sure-fire formula for disappointment, so obviously it isn't a useful solution. The problem here is that aluminum is a non-ferromagnetic material with a relative permeability value nearly identical to that of air—thus it's about as useful as air in corralling the stray magnetic field and preventing CRT image distortion. Display distortion continues virtually unabated.

For my third simulation (*Fig. 11*), I modeled another common suggestion: enclose the loudspeaker in a container of some sort. In this case I used copper as the material. Once again you see the field is anything but corralled, which is just what you would expect using yet another non-ferromagnetic material.

Copper has a relative permeability very close in value to that of aluminum, and the results from this FEA run reflect this. Any CRT caught within the field surrounding the copper box would suffer distortions just as it would with the aluminum shield modeled previously.

You could reasonably argue that other materials, such as steel, mumetal, and so on, could have been used to produce the modeled enclosure. But their effectiveness, practicality, predictability of results, and so on, when measured against cost and so forth still don't make their use worthwhile.

Besides, suppose you did find a material that could effectively shield the CRT monitor from the magnetic field surrounding the loudspeaker system. You'd need to encase the entire system in order to maximize effectiveness. And who wants to listen to a loudspeaker entirely contained within a metal box? Not very practical.

In my fourth FEA simulation (*Fig. 12*) I modeled the magnet structure with a second magnet (also known as a bucking magnet) of the correct size, shape, material, and orientation placed up against the original magnet structure. Here you can see that the magnetic field is very effectively corralled, certainly far better than in any of the preceding simulations. Best practices here dictate that using drivers with a built-in bucking magnet already in place is the correct way to prevent CRT-distorting magnetic fields getting at your TV or computer monitor.

The bonus? The presence of the buck-

FIGURE 8: Power dissipation among the Rsource components.

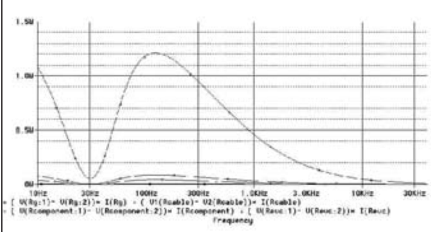


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FIGURE 9: Unrestrained magnetic field.

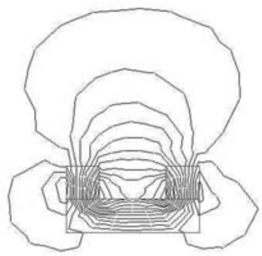

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TABLE 3: Gauge wire dimensions

	Length	Diameter (inches)	Area (cir mills)	Area (in2)
30-gauge wire	57.619′	0.01003	100.5	0.00007894

ing magnet can increase field density in the voice-coil gap, which, in turn, means increases in efficiency and lowered QES, as compared to its non-bucking equipped twin. Conversely, placing a cup shield made out of a ferromagnetic material around the magnet assembly will typically result in a reduction in field gap density, which results in reduced Bl, efficiency, and increased Q_{ES}—all because the cup provided a lower reluctance path for the flux to follow than that within the voice coil gap.

3. GOLD IS THE BEST CONDUCTOR

Often found buried in online discussions of cables and interconnects is the contention that gold is the best conductor from which to make said items. Reality is, whether or not gold (or any other metal, for that matter) is the best choice of conductor depends on the application for which it is intended.

I've put together a chart (*Table 2*) listing basic properties of several metals I've seen mentioned at one time or another in online discussions. From a material properties point of view, gold's most outstanding feature is that it's a noble metal and therefore does not react with the environment as the other metals do, which makes it a great choice where corrosion-resistant connectors are required.

A quick look at the chart shows it is not the least resistive or lightest of metals either—two reasons you don't see gold voice coils, especially when you consider that copper is less resistive, lighter, cheaper, and commonly available in wire form. To put the various metals into perspective-enhancing rankings, I constructed a chart which shows a variety of parameters for a theoretical voice coil, consisting of a 4-layer coil, wound with 30-gauge wire on a 2″ former.

Using:

$$R = \rho * l/A \ (\Omega)$$

where: R = resistance of sample at 20°C
ρ = specific resistance
l = length of sample
A = cross-sectional area of sample

to determine resistance of the conductor and using:

$$R = Rref * [1 + a * (T - Tref)] \ (\Omega)$$

where: R = conductor resistance at temperature "T."
Rref = conductor resistance at 20°C
a = temperature coefficient of resistance
Tref = reference temperature at which Rref is specified.

to determine resistance at various temperatures. And in each case, as I mentioned previously, 30-gauge wire with the dimensional properties listed in *Table 3* is used.

From *Table 4*, you can easily see that a voice coil made of either silver, copper, or OFC copper has a lower Revc than one made of gold. You can also see that these voice coils would be lighter than one made of gold. It is interesting to note that an OFC copper voice coil has a slightly *higher* resistance than the non-OFC version.

Silver, though the best conductor in

FIGURE 10: Magnetic field with aluminum shield.

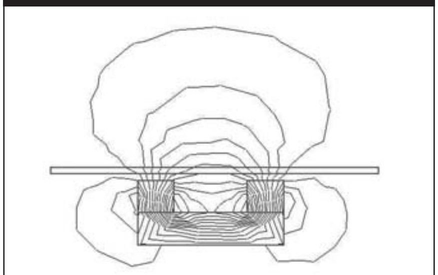

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FIGURE 11: Magnetic field with copper box.

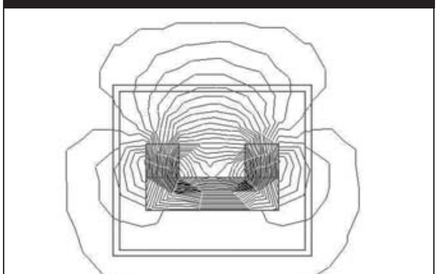

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FIGURE 12: Magnetic field with bucking magnet.

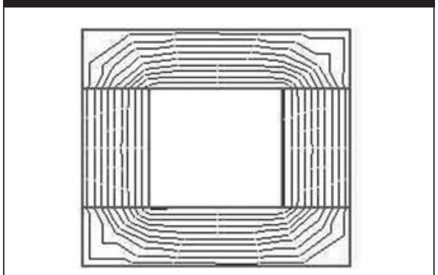

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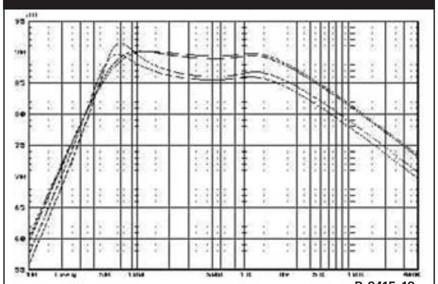
FIGURE 13: System response resulting from voice coils made of various metals.



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terms of exhibiting the lowest resistance, isn't often used as voice-coil wire because (aside from cost) the gain in driver efficiency as a consequence of lowered resistivity is more than offset by the loss of efficiency caused by the increase in voice-coil mass. Conversely, aluminum does find its use in tweeters because its comparatively lesser density makes for a lower moving mass voice coil, which offsets the decreased efficiency owing to its higher resistivity.

I was particularly interested in seeing how the weight differences between voice coils made of the differing materials would affect system dB SPL response and impedance, so I ran five simulations in LEAP. In each case I held Revc constant, varying BL, Mmd (diaphragm mass, in grams), and letting LEAP alter the remaining driver parameters. I then (virtually) placed them—one at a time—in the same enclosure and generated db SPL and impedance plots.

It's interesting to note in the dB SPL graph (*Fig. 13*) that when Revc was held constant, the drivers sporting voice coils made from aluminum and gold (the lightest and heaviest materials modeled) had a response ~3db lower than those systems modeled with either version of copper or silver. Silver produced the highest reference efficiency system, but only a small fraction of a dB above either of the coppers.

In looking at the impedance chart, you see the two coppers present nearly identical curves (*Fig. 14*). Aluminum had the lowest Zpeak (~31Ω) of all samples and silver had the highest (~81Ω). Gold presented an impedance peak located between that of aluminum and the two coppers.

When you take into consideration other issues important in the manufacturing process (cost, availability, resistance to mechanical and thermal stress, solderability, and so on) and add them in to the equation with copper's comparatively low resistance and light weight, it's easy to see why it features so prominently in audio. Given the preceding analysis, I think it's fair to say that for applications other than those requiring a high degree of corrosion resistance, gold is not the best conductor around, and in most other cases good ol' copper (OFC or not) is the best choice.

FIGURE 14: Metals properties table.

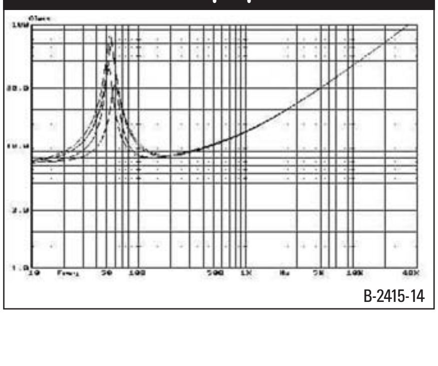

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TABLE 4: Various wire materials and their effects on resistance, attenuation, and voice coil weight

	Resistance (Ω) at 20°C	Attenuation Loss* at 20°C (dB)	Resistance (Ω) at 100°C	Attenuation Loss* at 100°C (dB)	Weight (gm)
Silver (Ag)	5.345	-4.44	6.97	-5.443	9.383
Copper (Cu)	5.862	-4.774	7.653	-5.830	8.01
OFC Copper (Cu)	5.896	-4.796	7.815	-5.919	7.95 - 7.996
Gold (Au)	7.655	-5.8312	9.737	-6.915	17.280
Aluminum (Al)	9.31	-6.704	12.215	-8.052	2.413

*Referenced to 8Ω

4. BASS REFLEX IS MORE EFFICIENT THAN TOTALLY ENCLOSED BOX

Here's one that's been around far longer than any Internet online forum! To sort the facts from fiction, I ran five systems simulations in LEAP, using a driver with the specs listed in *Table 5*.

In the first simulation, I modeled a totally enclosed box system, used as a baseline against which all subsequent modeled systems were compared. I then

TABLE 5: Test Driver Specs

SPLo=89.93dB	SPLi = 89.29dB	SPLi = 89.82dBI	
no = 0.62%	ηI = 0.53%	Eg = 2.83V	
Rem = 3.56Ω	Lem = 1.264mH @ 1kHz		
Rem = 34.26Ω	Lem = 0.457mH @ 20kHz		
Znom = 8.000Ω	Sd = 0.0349m²	Fi = 30.218Hz	Hvc = 15.000mM
Revc = 7.093Ω	BL = 12.7619 T • m	Fo = 31.328Hz	Hag = 7.000mM
Krm = 4.779mΩ	V_{AS} = 89.0391 ltr	Q_{MS} = 6.054	Xmx = 4.000mM
Kxm = 24.731mH	Cms = 514.7923μM/N	Q_{ES} = 0.430	Cmx = 4.000mM
Erm = 0.756	Mms = 50.1364gram	Q_{TS} = 0.401	Cmo = 1.000
Exm = 0.660	Mmd = 46.3875gram	Pmx = 100.000	Wrms Θvc = 2.500C/W

ran three subsequent simulations, each representing some permutation of the first baseline system. I then ran a fifth and final simulation, modeling a properly designed and tuned BR system. The modeled systems' specs are shown in *Table 6*.

I started with a comparison of the baseline system to a system in which Vb was doubled, with all other design parameters held constant. This doubling of the net internal cabinet volume used for the baseline design did very little to change overall response and nothing in the passband reference efficiency region as shown in *Fig. 15*. (As you read through the graph data, keep in mind that each vertical dB SPL axis is scaled in 1dB units).

I then re-ran the simulation, this time modeling a system with a net internal cabinet volume ten times larger than that of the baseline system (*Fig. 16*). Even with a one order of magnitude increase in net Vb, I observed no change in η_{0dB} of the system; it still hovers extremely close to that of the driver.

Next, I took the baseline TEB system and virtually cut a port in the cabinet. The port modeled had a 0.75″ depth, and a cross-sectional area of 0.5 * Sd (.017545m^2). All other parameters were, as before, held constant. I then re-ran the simulation, producing the result shown in *Fig. 17*.

There are some noteworthy items in this graph. First, you see the mid-band reference efficiency of the ported system has actually *dropped*, while at the same time a ~+10dB local maximum has appeared at just a bit above 100Hz.

I've included beneath each graph an area under curve (AUC) value generated by performing an integration on the response plot from 10Hz to 40kHz. The |Δ| value represents the absolute value of the percentage difference found when comparing the AUC value of the baseline TEB versus each of the other four systems modeled. I included the

FIGURE 15: Response plots for baseline TSB and 2× VB TEB. Baseline AUC: 3138748 2× TEB AUC: 3138695 |Δ| = .001%.

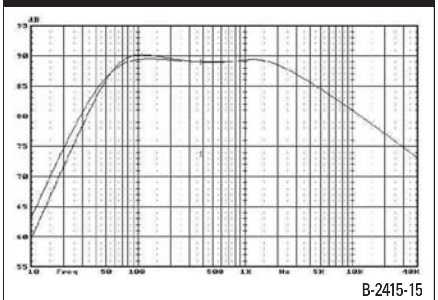

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FIGURE 16: Response plots for baseline TEB and 10× VB TEB. Baseline AUC: 3138748 10× TEB AUC: 3138627 |Δ| = .0038%.

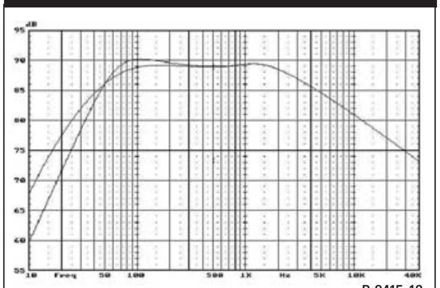

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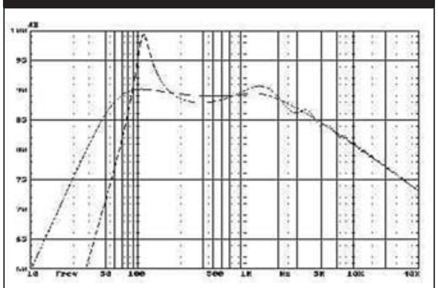
FIGURE 17: Response plots for baseline TEB and ported TEB. Baseline AUC: 3138748 Ported TEB AUC: 3138952 |Δ| = .006%.



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AUC as had there been any substantial differences in the resulting simulation η_{0dB} values, it would have shown up as a $|\Lambda|$ far larger than the vanishingly small values shown.

Last, I compared the baseline TEB response with that of a BR system, featuring, as in each preceding case, the test driver specified above (*Fig. 18*). Here you observe the bandwidth extension which you would expect for a properly designed and tuned BR cabinet. Once again, there is no change evident in the observed passband η_{0dB} value.

From these graphs you can conclude that simply cutting a hole in a TEB cabinet or increasing the size of the cabinet will not increase η_{0dB} values. You've also seen that, in some cases, such modifications can slightly decrease system η_{0dB}.

You've also observed you can design a TEB and BR system with the same driver and come up with a BR system that sports an extended LF response when compared with that of the TEB, but that won't change the η_{0dB} value observed in either system, as the graphs clearly indicate. An increase in bandwidth—yes, but a change in reference efficiency—no.

To understand why, for each of the systems modeled, the η_{0dB} values determinedly remained within a small fraction of a dB of the test driver's reference efficiency value, take a look at the mathematical underpinnings of driver and system efficiency. You'll also see why system η_{0dB} hovers near or below driver η_{0dB} but never exceeds the driver's η_{0dB} value.

From:

$$\eta_0 = \frac{\rho_0}{2\pi c} * \frac{B^2 l^2}{Revc} * \frac{Sd^2}{Mms^2}$$

you can calculate a driver's reference efficiency, where:

η_0 = reference efficiency of the driver, dimensionless
ρ_0 = the density of air at STP, 1.204kg/m^3 at 20°C
c = speed of sound at STP, 343.4m/s at 20°C
B = magnetic flux density in the driver air gap, in teslas
l = length of the voice coil winding in the gap, m
Revc = DC resistance of the driver voice coil, ohms
Mms = mechanical mass of the driver diaphragm assembly, including air load, kg
Sd = effective projected surface area of the driver diaphragm, m^2

From:

$$\eta_0 = k_\eta * f_3^3 * Vb$$

you can calculate the reference efficiency of a closed box system where:

η_0 = reference efficiency of the system, dimensionless
k_η = efficiency constant, dependent upon chosen alignment, $s^3 m^{-3}$, given by:

$$k_\eta = \frac{4\pi^2}{c^3} * \frac{fc^3}{f_3^3} * \frac{Vat}{Vb} * \frac{1}{Qec}$$

fc = closed box system resonant

FIGURE 18: Response plots for baseline TEB and BR system. Baseline AUC: 3138748 BRLEF AIC: 3139468 $|\Delta|$ = .0229%.

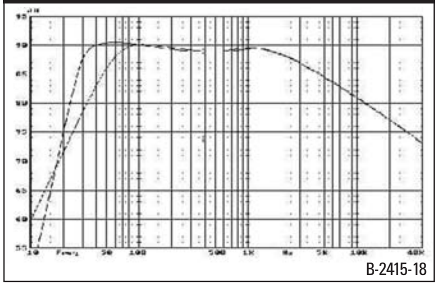

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TABLE 6: Observed η_{0dB} (@ 500Hz), Vb (ft^3) for the various systems modeled

	Qb	Vb (ft^3)	Observed η_{0dB} (at 500Hz)	Notes
Test Driver	-	-	89.29dB	Raw driver
Baseline TEB	2	0.9046	89.29dB	100% stuffed
2× VB TEB	2	1.809	88.94dB	Baseline TEB VB*2
10× TEB	2	18.09	88.87	Baseline TEB VB*10
Vented TEB	2	0.9046	87.91dB	Port area = 0.5Sd
BR system	7	2.154	88.95dB	fb = 31.55Hz

frequency
f3 = –3dB cutoff frequency of the system
c = speed of sound at STP, 343.4m/s at 20°C
Qec = system electrical Q at fc
Vb = net internal volume of enclosure
Vat = total system compliance expressed as equivalent volume of air, l

For closed box systems, k_η maxes out at ~$2.0*10^{-6}$. This figure represents a maximum performance limit and can be reached only by employing a lossless system, based on the C2 alignment.

For vented systems you have, once again:

$$\eta_0 = k_\eta * f_3^3 * Vb$$

where:
η_0 = reference efficiency of the system, dimensionless
k_η = efficiency constant, dependent upon chosen alignment, s^3m^{-3}, given by:

$$k_\eta = \frac{4\pi^2}{c^3} * \frac{fs^3}{f_3^3} * \frac{Vas}{Vb} * \frac{1}{Qes}$$

fs = driver resonant frequency
f3 = –3dB cutoff frequency of the system
c = speed of sound at STP, 343.4m/s at 20°C
Q_{ES} = driver electrical Q at fs
V_{AS} = volume of air having same acoustic compliance as driver suspension
Vb = net internal volume of enclosure

For vented systems, k_η maxes out at ~$3.9*10^{-6}$. This figure represents a maximum performance limit and can be attained only by employing a lossless vented system, based on a k = 0.5, C4 alignment.

In all three cases, you can convert η_0 values to power sensitivity in decibels by:

$\eta_{0dB} = 112.2 + 10 * \text{Log}(\eta_0)$
(dB SPL/1W/1m)

or, alternately, converted to percent by:
$\eta_{0\%} = 100 * \eta_0$ (%)

Efficiency, broadly defined in this context, is the ratio of acoustic power out to electric power in: $\eta = \frac{P_A}{P_E}$

where both PA and PE are in watts.

The two system reference efficiency equations say that enclosure volume, cutoff frequency, and maximum reference efficiency are interdependent. Small refers to this as the "Efficiency-Bandwidth-Volume Exchange." Given the alignment type and losses present, η_0 can be maintained while altering either f3 or Vb only by altering the value of the remaining factor. Want a lower f3? You'll need to increase Vb. Want a smaller cabinet? You can expect f3 to rise, presuming, of course, that you want to maintain a particular η_0 value constant (or ratio of acoustic power out to electric power in).

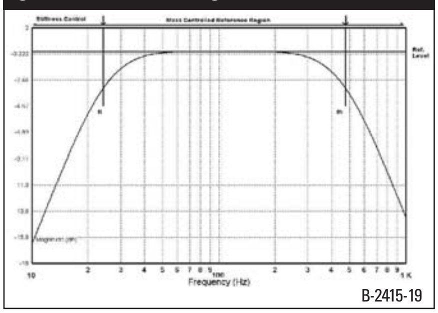
Keep in mind that the calculated system η_0 values represent an ideal performance maximum: the best you could hope for, given a specific alignment resulting from a specific design for a specific driver. In practice, actual system η_0 values are lowered or constrained by such factors as driver mechanical losses, enclosure losses, and employing alignments other than those mentioned previously as being maximally efficient. Therefore, it's not difficult—by choice or chance—to design a system that exhibits a lesser actual η_0 value.

Loudspeaker design is a study in artful compromises; what you trade away in one area to gain in another depends upon, among other things, what your design priorities and goals are. If, in this case, for a given driver every design permutation you model delivers insufficient η_{0dB} values, the only way to increase the values would be to switch to a more efficient driver.

Above resonance, but below fh, the driver is operating in its inertial mass-controlled reference efficiency passband. As such, in this portion of its output spectrum, the cone is mass-limited and the driver functions as a constant acceleration device, producing constant volume velocity. An enclosure does not change the mass of the driver cone, so it cannot affect efficiency as constrained/controlled by cone mass. The air within the cabinet does not provide resistance to the motion of the cone; if it did, varying cabinet size would produce varying observed η_{0dB} levels. You do not observe such variations across the five simulations (even in the case where cabinet size is increased by a factor of 10).

Given that a driver's reference efficiency is taken from the mass-controlled region of its response, a driver's efficiency is independent of an enclosure's volume, whether or not said enclosure is vented. Neither does an enclosure alter a driver's Bl, Sd, or Mms. So essentially you see no real variations in η_{0dB} levels across each of the five simulations because the cabinet does not affect or otherwise alter the driver parameters that determine its reference

FIGURE 19: Bandpass response of a generic electromagnetic driver.



efficiency. Hence you never see a system sporting η_{0dB} levels greater than that of the driver, but given a variety of factors you can see a cabinet/driver combination that lowers η_{0dB} levels that could otherwise be attained.

5. THE PERFECT DRIVER. . .

would be infinitely stiff and completely massless.

I think this myth has survived as long as it has because, at first glance, the assertion seems to make sense; after all, a driver that is infinitely stiff and has no mass should have no problem responding perfectly and instantly to every electrical impulse fed its inputs, right? Let me show you what a bit of examination behind the scenes of the typical bandpass response of moving coil driver turns up (*Fig. 19*).

You can divide the response curve roughly into three regions, each demarcated by fl (lower resonance) and fh (upper resonance).

Below fl, stiffness (or its inverse, compliance—as supplied by the driver's suspension—expressed as Cms) predominates in limiting the motion of the cone and output is proportional to frequency (see Joseph D'Appolito, *Testing Loudspeakers*), which, below resonance, means a rolloff of 12dB/octave as frequency drops. In this region the driver functions as a constant excursion device.

At fl, output depends on resistance, including Rsource and Revc. The frequency at which fl occurs is determined by the moving mass of the driver. And as the theoretical moving mass of the driver $\rightarrow 0$, fl approaches ∞ Hz. As shown by:

$$fs = .5p * (1/(Cms * Mms))^{0.5} \qquad \text{(Hz)}$$

where:

fs = free air resonance of driver, Hz
Cms = mechanical compliance of driver, m/N
Mms = effective mechanical mass of driver diaphragm, in kg

Between fl and fh is the mass-controlled reference region of the driver. In this portion of its output spectrum, the cone is mass-limited and the driver functions as a constant acceleration device, producing constant volume velocity. Radiation remains essentially hemispherical and directivity, constant.

At fh, like fl, resistance plays the controlling role. Fh can be determined by:

$$fh = \frac{\omega \bullet LevcB^2I^2}{\omega^2 \bullet Levc^2 + (Rg + Revc)^2}$$

and total resistance at fh can be found by:

$$Rtotal = \frac{(Rg + Revc) \bullet B^2I^2}{(Rg + Rc)^2 + \omega^2 \bullet Levc^2} 10$$

So where's the problem with the infinitely stiff/massless driver?

By setting stiffness to ∞, fl is pushed up to ∞ Hz (besides sounding painful in an abstract sort of way), which means that since response rolls off at 12/dB per octave, by the time frequency has dropped to within the audible range response is $-\infty$ dB down, hence no output.

Above fl = ∞, the incredible driver is, predictably, functioning as a constant acceleration device generating a flat frequency response, but as it's all happening at a frequency of ∞ Hz, there's no audible output. The perfect driver remains—as far as human hearing goes—silent. There exists a whole host of other technical issues that would contribute to the driver's zero output (e.g., out-of-phase cancellation), but just focusing on Cms = 1/8 and Mms = 0 are, in and of themselves, sufficient to silence the myth.

Ferreting out the facts behind a myth—or any facet of loudspeaker design, for that matter—can be enjoyable, satisfying, and enlightening. Like a detective story in which every clue is important, you can find yourself developing an almost childlike curiosity when investigating the facts using whichever tool you have at hand: mathematics, CAD, your calculator, or a workbench with a bunch of analog test gear on it. The Internet, while providing forums for the propagation of audio myths, is also a formidable tool in providing many resources useful to sorting facts from fiction. Perhaps the greatest benefit of all such research is that, in the end, you can only gain in understanding. **aX**