Designing Bass Reflex Loudspeaker Enclosures

   Loudspeaker enclosures can take the form of an almost endless number of varieties, from the simple sealed box (often called 'infinite baffle', which they are not) to the exotic horn, which can be very complex to construct. Between these two extremes falls the phase inverter, better known as the bass reflex enclosure. The bass reflex is the dominant design for most high efficiency bass drivers, for a number of reasons.
   First, a typical high efficiency woofer has a highish free air resonance (Fs). If this type of a driver is put in a sealed box, the system resonance (Fb) becomes too high for decent bass response.
   By using a ported enclosure (bass reflex), the energy generated by the back side of the loudspeaker cone is put to useful work, by adding it to the radiation generated from the front of the cone. The port in the enclosure inverts the phase of this energy, so it is in phase with the energy from the front of the diaphragm. Above the port tuning frequency, the impedance of the port prevents the back wave from emerging, and below the tuning frequency, the emerging wave front becomes out of phase, but at this point it is no longer of importance.
   Designing bass reflex enclosures was at one time pure guesswork, luck, and mostly, trial end error. Then in the early seventies, A.N.Thiele and Richard H. Small devised a set of formulas to predict how a driver would perform in any given box. Thiele was the senior engineer of design and development for the Australian Broadcasting Commission and was responsible at the time for the Federal Engineering Laboratory, as well as for analyzing the design of equipment and systems for sound and vision broadcasting. Small was, at the time, a Commonwealth Post-graduate Research Student in the School of Electrical Engineering at the University of Sydney.
   Thiele and Small devoted considerable effort to show how the following parameters define the relationship between a speaker and a particular enclosure. However, they can be invaluable in making choices because they tell you far more about the transducer's real performance than the basic benchmarks of size, maximum power rating or average sensitivity.

Thanks to the pioneering work of Thiele and Small, we can now use simple mathematical formulas to predict the performance of any given driver in any sized box. You will find all of the Thiele / Small parameters listed at the end of this paper. Only a few are typically used to calculate enclosures.

The formula for calculating the ideal box size for a 4th order alignment (giving a maximally flat response) is:

$$Vb=(15)(Vas)(Qt^{2.87})$$

Where Vb = volume of the box (in liters or cubic feet)
        (15) is a constant
        Vas is the equivalent compliance of the driver
        Qt is the total Q of the driver (also called Qts)

You will find all of this info if you examine the datasheet for your driver. Most manufacturers now provide this data.

Let us work an example, using the Selenium WPU1507 driver. If we check the specifications for the driver, we find that it has a Vas of 5.33 cu. ft. and a Qts of 0.43

  With these numbers, lets go through the formula.

$$Vb=(15)(5.33)(.43^{2.87})$$

 On your calculator (Windows has one if you don't. View the scientific mode) find the solution for .43 raised to the power of 2.87. This is the button on your Windows calculator with this symbol x^y. So, enter 0.43, then click the x^y button, and enter 2.87, then click =. You will get a long number (0.0887267…etc).
  With this number still on you calculator, simply multiply by the other two numbers. We will continue with our example.

$$Vb=(15)(5.33)(0.0887267)$$

 Multiply 0.0887267 x 5.33=0.472913311

Vb=(15)(0.472913311)

Multiply 0.472913311 x 15 = 7.0936…

We will round this off to 7.0937 cubic feet (ft^3). Since we used cubic feet for Vas, our answer is in cubic feet. If we had used liters, then our answer would be in liters.

We now know the box size that will give us the ideal response curve (maximally flat). Now we need to find out at what frequency the bass response starts to roll off (the −3db point), telling us how good of bass response we can expect, and if it meets out requirements.

The formula for calculating the 3db down point is:

$F3 = 0.26(Fs)/(Qt^{1.4})$

The WPU1507 has a free air resonance (Fs) of 36Hz, so 36 x .26 = 9.36

The WPU1507 has a Qt of 0.43, so .43 to the power of 1.4 (remember the x^y button?) = 0.30680034….

So using these numbers in our formula: F3 = 9.36/0.3068

So, F3=9.36 divided by 0.3068, or about 30.5 Hz. This is a pretty good F3, and this box will give great, solid bass response!

We have been calculating box size and bass cutoff point for a vented (bass reflex) enclosure. Since this type of enclosure uses a vent TUNED to some (as yet unknown) frequency, we now need to calculate the box tuning frequency (called Fb).
The formula for calculating Fb is:

$Fb = 0.42(Fs)/Qt^{0.9}$

Where 0.42 is a constant
Fs = 36Hz
Qt= 0.43

Lets first solve $Qt^{0.9}$

Qt = 0.43, so, $0.43^{0.9}$ = 0.467866…., or 0.4679, rounded off.

Next, solve 0.42 x Fs, or, .42 x 36, which = 15.12, so our formula looks like this:

Fb = 15.12/0.4679

15.12 divided by .4679 = 32.31, so our box tuning frequency is 32 Hz.

We now know that a box giving us a maximally flat response using the Selenium WPU1507 driver will need to displace 7.0937 cubic feet tuned to 32Hz, giving a −3db point of 30Hz.

The last formula we need is to calculate our port size (or duct). A duct is a port (hole) that has length. All ports are ducts, even if it is only the thickness (length) of the box material (typically ¾ in.).

The formula for determining the duct length is:

$Lv = (((1.463)(10^7)(r^2)) / ((Fb^2)Vbin))) -1.463\,r$

Where Lv = duct length
r = radius of vent (inside)
Fb = box tuning freq (32)
Vbin = box volume in cubic inches . 1 cubic foot = 1728 cubic inches.

 For our example, lets go back to the first set of calculations we did for the WPU1507 in a 4th order Maximally flat box of 7.0937 cubic feet.
   The vent can be any shape, but the area needs to be converted to the equivalent diameter for the formula. For instance, we use a 3x12 inch vent on this example system, which is a 36 square inch vent. The equivalent round vent would be about 6.77 inched in diameter (area of a circle (round vent) is $A = pi \times r^2$, where A = area, pi = 3.14159, and r^2 is radius of circle squared).
So, for our 6.77 diameter (equivalent) vent, r is equal to 3.385 inches.
Since this formula uses cubic inches for box volume, we need to calculate this. Our box is 7.0937 cu. ft., so, 7.0937 x 1728 = 12257.9, or 12258 cubic inches.
Using these numbers, our formula looks like this:

$$Lv = ((1.463)(10^7)(3.385^2)/(Fb^2)12258)-1.463(3.385)$$

3.385 squared = 11.458225
Fb = 32, so 32 squared = 1024

Plugging these numbers in has our formula looking like this:

$$Lv = ((1.463)(10^7)(11.458225)/(1024)(12160))-1.463(3.385)$$

10^7 = 10000000
1.463 x 10000000 x 11.458225 = 167633831.75
1024 x 12258 = 12552192

This makes our formula look like this:

$$Lv = (167633831.75/12552192)-1.463(3.385)$$

167633831.75 divided by 12552192 = 13.3549
1.463 x 3.385 = 4.952255

So now our formula is reduced to:

$$Lv = 13.3549 - 4.952255$$

13.4626 - 4.952255 = 8.40 inches.

So, with an enclosure volume of 7.0937 cubic feet tuned to 32 Hz with a port of 36 square inches, the port duct needs to be 8.4 inches long.

Whew!! Now those weren't that bad, were they?

So, what's the next step? Just drawing up a box with the required box volume, and start cutting holes in it?

 Well, no. First we need to calculate the box volume we need.

Huh?? Didn't we already calculate box volume (Vb)?

 Well, yes, we did. The Vb we came up with is our required (usable) box volume. If we stick our woofer, midrange horn and driver, tweeter, ducted port, and bracing into this box, we will loose all of the volume displaced by those items, and our usable volume will be much less than we intended. Therefore, we need to *add* the volume of all those items to our Vb to find our final box volume.
   Let us define the other components in our system. We have chosen the D405 midrange compression driver mated to the HM3950 horn. We like the D405's smooth midrange from its phenolic diaphragm, and we like the 60 degree dispersion pattern of the horn. Which minimizes room reflections. We will add the DT150 horn/driver

combination for the high frequencies. Its 60 degree pattern nicely matches the midrange horn, and the phenolic diaphragm is nice and smooth, also. You may choose different components, depending on your own needs, and that is fine. For our example, we will use the components mentioned.

   If you check the specifications for those items on the datasheets, you will find a listing for the volume displaced by the items. For instance, the WPU1507 woofer displaces 0.23 cu. ft. The D405, 0.098 cu. ft., the HM3950, 0.095 cu. ft., and the DT150, 0.021 cu. ft.
   All together, these items displace a total of:

.23 + .098 + .095 + .021 = 0.444 cubic feet.

   Now for the port. We are using a port of 3 inches by 12 inches by 8.4 inches deep. This port is made from ¾ inch thick material, which also needs to be calculated in. The depth of the port, 8.5 inches, is from the outside surface of the enclosure.
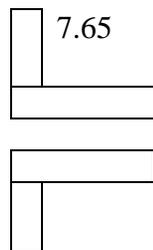If we use ¾ inch thick material for our enclosure, then 7.65 inch of the duct will be on the inside of our enclosure. (7.65 + 0.75 = 8.4 inch total length. If our duct is made with ¾ inch thick material also, then what we need to calculate is:
  3 inch high duct + ¾ inch material on the top and bottom = 4 ½ inches.
  12 inch wide duct + ¾ inch material on each side = 13 ½ inches.
  7.65 inch deep duct on the inside of out enclosure

Therefore, 4.5 x 13.5 x 7.65 = 464.7375 cubic inches, or .2689 cubic feet. (remember, there are 1728 cubic inches in a cubic foot, so 464.7375 divided by 1728 = .2689
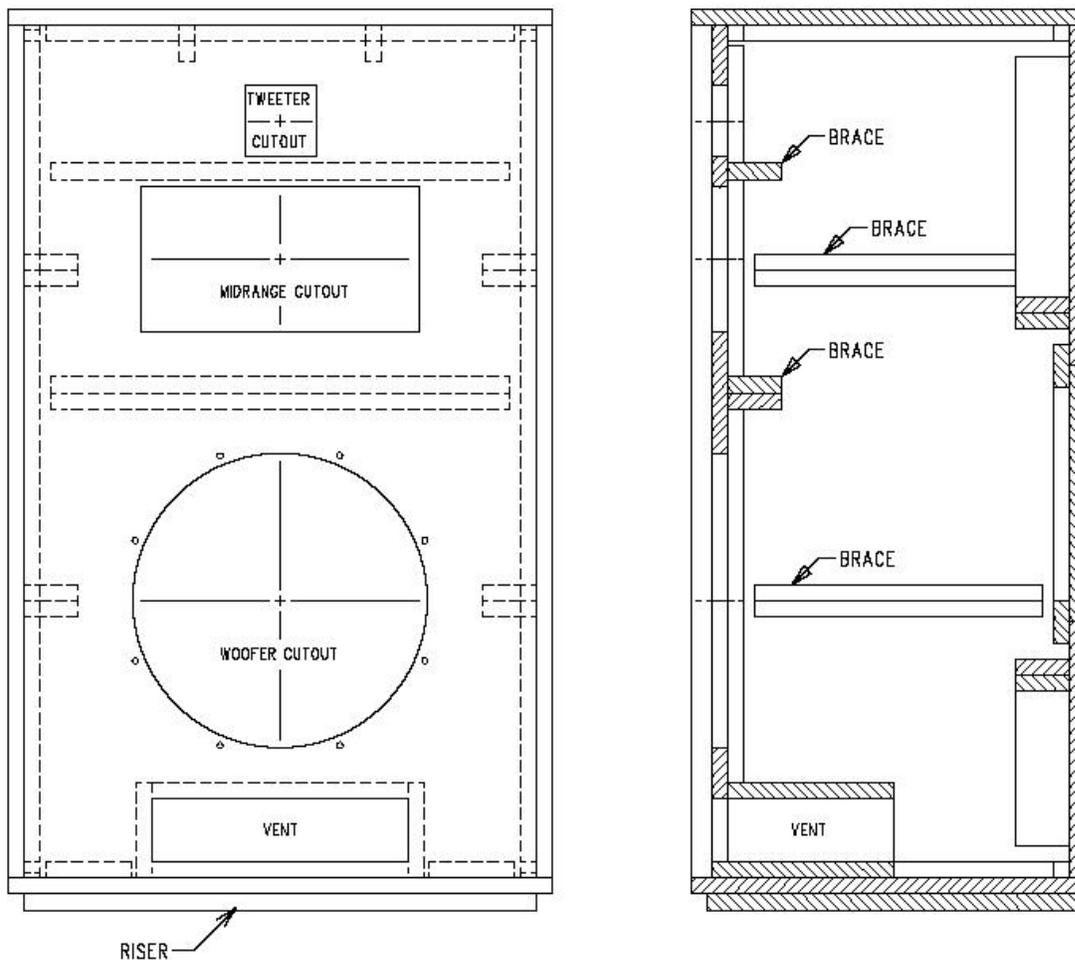

So now, we add this to the volume displaced by our components: .2689 + .444 = 0.7129 cubic feet. Added to our Vb of 7.0937, we get 7.806 cubic feet. Since we are going to design our box in inches, lets convert this to cubic inches, which is 13488.768, or 13489 cubic inches.

Is that it? No, we need to calculate bracing, as well. The WPU1507 will develop a tremendous amount of power, and can flex a poorly braced box, which is undesirable. To get an idea of the size of our braces, we need to estimate the box size.
   Vb of our box simply states the displacement of the enclosure, but nothing about its shape. What shape do you need it to be? If you don't have a specific requirement on shape, let us look at this from a performance side of things. The ideal shape for a loudspeaker is a ratio of (2d) x (3d) x (5d), with d being an unknown number at this point. Typically, 2d is the depth, 3d is the width, and 5d is the height. If you multiply 2 x 3 x 5, you get 30. So, if we divide our box volume of 13489 cubic inches we get 30 cubic units of 449.633 cubic inches each. To convert this to a usable linear dimension, we need to find the cube root. So, raise 446.566 to the power of 0.333333, and we get 7.66…Lets add a bit, since we know this is still a bit smaller than desired (because we have not yet calculated the bracing). Lets round this up to 8.
   OK, so lets base our numbers now on a box with inside dimensions of 2x8 by 3x8 by 5x8, or 16 x 24 x 40 inches inside.
When building a box, you usually have glue blocks as well as bracing. Glue blocks are usually made from the same material as the box, ripped with a saw, so one dimension of a glue block will be .75 inch thick as well. Lets look at a clip from the "Typical box construction" file. It shows the typical bracing needed to ensure a rigid enclosure.

You can get an idea what we think is needed as far as bracing is concerned. The amount, and placement of the bracing inside your own enclosure is up to you. Going by our plans, we can calculate how many cubic inches is taken up by bracing. That number comes to about 720 cubic inches. Added to our previous total of 13489 cubic inches, we now have a grand total of 14209 cubic inches, or 8.223 cubic feet. You can see that it is important to calculate the displacement of everything inside the box. If we had not done that, but just built a box of 7.0937 cubic feet, and then installed all of the components, the actual useable volume would have been over a cubic foot less than we had thought, and we would not have achieved our target performance.

Let me restate the importance of a rigid enclosure. While the amount of bracing you use is up to you, don't skimp. What do you build an enclosure from? The most common materials are plywood, particle board, or MDF. The most common thickness is ¾ inch. Some people use double thickness material all around. That's fine. Some have actually built the boxes from concrete. That certainly makes a nice rigid enclosure, but it is hardly practical for most people. Find your own limits as far as complexity and weight are concerned.

If this enclosure is going to move around a lot, (such as a loudspeaker for a touring band), then the best choice is plywood. Plywood is more forgiving when dropped, where particle board or MDF would crack and crumble. Use a good grade of ¾ inch thick material. It should be void free. Plywood is more resonant than particle board or MDF, so it needs a bit more bracing than the other materials.

If the enclosure is for an application where it is only moved around occasionally, like a home setting, then particle board or MDF is a better choice, since it has better damping characteristics. If you are cutting this material yourself, using a table saw or radial arm saw, invest in a good carbide tipped blade. Particle board and MDF will dull a regular blade quickly. If you are designing your own enclosure (instead of using plans), draw it out on paper first. Drawing up your own set of plans can save you problems in the long run! The purpose of this paper isn't to give detailed plans for a given design, but to give general guidelines for building a loudspeaker. However, let us state right now, that working with power saws and drills can be very dangerous if proper safety rules are not adhered to. If you are not familiar with using power tools, get help from someone who is. Also, cutting wood with a power say generates A LOT OF NOISE! Wear hearing protection! The benefits of a high resolution loudspeaker is lost on people who are deaf! Protect your hearing!

At this point, you may want to review the details of the Maximally Flat 4th order box for the Selenium WPU1507 on the enclosure page, as it covers a lot of this in a different way.

Install all of the glue blocks first. They are installed on the two sides, the top, and the bottom. The braces are not installed until the 5 sided box is assembled.

Assemble the box using white glue, or yellow carpenters glue (like Elmers). Screws are not required, since the glue will dry and make a joint much stronger than the screw.

We like to start by assembling the 4 sided box (2 sides, top and bottom), using a couple of band clamps. Lay the pieces so the enclosure is laying on its back. Apply glue to all four pieces where they will come together, and tighten the band clamps until the glue squishes out from the joints. Apply glue at this time to the top, bottom and side pieces that will contact the front baffle, and install the front baffle, also. This will 'square' the 4 sided box assembly. Use heavy items to weight down the front baffle. Let the assembly dry overnight.

Once the assembly is dry, remove the weights and the band clamps, and turn the 5 sided box upright. Using a flat bladed screwdriver, or a chisel, clean any glue drips from the areas where the rear baffle will go. Caulk the inside seams of the 5 sided box using window caulk, or RTV. You want to insure that the box doesn't have any leaks, other than the intended ones (the port). This is the time you want to cut out the front baffle for your driver and horn units. Draw the cutouts in pencil, and cut them out with a jigsaw. Pre-drill the screw holes, as well. If you are going to use 'T' nuts, install these now, too. Assemble the port pieces at this time, and install the bracing. Give the glue ample time to set up before disturbing the weights holding them in place. Install the braces, etc. on the inside of the rear baffle at this time, also. Examine the outside of your 5 sided box. If you have any corners that have broken, or crumbled, repair these now, prior to finishing or veneering the enclosure. The best way to repair particle board or MDF is to take some sawdust and mix it with some white glue. Apply this paste to the crumbled area, shaping them with a flat object, like a putty knife or flat screwdriver blade. After this paste has dried, sand it with a sanding block until it has the proper profile. This stuff is tough! It will be far stronger than the original particle board.

After the outside of the 5 sided box has been 'prepped', paint the front baffle black or dark grey. We like satin (or matte) black. True flat black never looks as black as the satin finish type, although after the grill cloth is on, it doesn't really matter. Give it a couple of coats. This will help everything to disappear behind the grill cloth. (If you leave the baffle unpainted, you will see the speakers through the grill cloth).

Now, you are ready to veneer the enclosure. We go to Tape-ease for our wood veneer. They are on our 'Links' page. They have every kind of wood veneer you could want. We recommend using the 10 mil veneer, since it makes corners disappear easier then using the 20 mil veneer. Once you have selected your veneer, and received it in the mail, lay it out flat. Take a bit of time to plan how you are going to apply it, grain wise. Do you want your two boxes to be finished in a 'mirror image'? If so, plan your veneer cutting appropriately.

We are not going into detail on the method of veneering in this paper, since this is intended as a guide to general construction methods. (See the Veneering download for a more in depth talk on the subject).

After the outside surfaces have been veneered, apply your chosen finish. When this has been completed, and it is dry, give the front baffle one last coat of black paint. You may want to paint the rear baffle, too.

You are now ready to install your loudspeaker components. We like to use RTV to seal the units, but you can use rubber gasket material, or whatever of your choice. Be very careful with a screwdriver around the driver units. Many times have people had a sinking feeling when the screwdriver blade slipped off the screw head and plunged through the driver surround! Go slowly here, and you should be OK. If you are still too nervous, make a 'shield' from scrap material.

Once all of the driver units have been installed, it is time to apply damping material to the top, sides, bottom, and rear baffle of the enclosure. We like to use polyester batting instead of fiberglass. Go to a fabric shop and get the stuff they use to stuff quilts. Just use white glue to glue it to the inside surfaces of the enclosure. One layer thick is all that you need. Do not obstruct the port. You do not need to apply it to the inside of the front baffle, but if you wish to, it will not hurt anything. This material helps absorb the rear radiation from the woofer at the higher frequencies. Now it is time to wire the driver units to the crossover network, and the terminals. This will probably require the rear baffle to be moved close to the assembly, since connections to the outside world are probably through the rear baffle. Make sure any wiring will not rattle or cause any buzzing. If in doubt, wrap them in polyester batting. After all wiring has been done, but before gluing in the rear baffle, do a low level check. Hook the speaker to your amplifier, and at low volume, play music and make sure all driver units are working as expected, and controls (such as level controls, if used) are working properly. If not, check all connections until you find the problem, and correct them. After you have verified that everything is working properly, lay the box down on its front, and apply glue to the rear baffle glue blocks. Don't skimp. Then install the rear baffle, using weights to keep it pressed firmly in place. Let them sit overnight.

After the rear baffles are installed, turn the loudspeaker units upright, and get them positioned in your listening room. They work best when 'toed in' a bit toward the listening area. Play music you are familiar with, and adjust level controls for the best balance. The midrange and tweeter units will certainly have to be 'turned down', since they put out MUCH more than the bass unit. It is now time to 'voice' the units (equalize), if you are going to do

that. If you are very lucky, you can achieve good balance simply using the 'L' pads on the loudspeakers. If you want it even better, or if you have a problematic room, equalization will be necessary. See the paper 'Voicing a Loudspeaker System'.

This paper is not expected to be the only source of information on building a high quality loudspeaker system, but as a fairly brief overview on the subject. The more research you do, and the better your understanding of the subject, the better prepared you will be. Building a loudspeaker is not difficult, if the basic rules are applied. Even if your woodworking skills are few, you can still assemble a system that will sound great, even if it looks less than great (hide them behind a grill).

You may want to hire the services of a cabinet maker to build your enclosures. Whatever works is great. Even having a cabinet maker build your boxes, you will still most certainly save money compared to buying a ready made system of equal quality ($5,000 or more!)

Here is a list of all the Thiele/ Small parameters:

Fs This parameter is the free-air resonant frequency of a speaker. Simply stated, it is the point at which the weight of the moving parts of the speaker becomes balanced ill certainly with the force of the speaker suspension when in motion. If you've ever seen a piece of string start humming uncontrollably in the wind, you have seen the effect of reaching a resonant frequency. It is important to know this information so that you can prevent your enclosure from 'ringing'. With a loudspeaker, the mass of the moving parts, and the stiffness of the suspension (surround and spider) are the key elements that affect the resonant frequency. As a general rule of thumb, a lower Fs indicates a woofer that would be better for low-frequency reproduction than a woofer with a higher Fs. This is not always the case though, because other parameters affect the ultimate performance as well.

Re   This is the DC resistance of the driver measured with an ohm meter and it is often referred to as the 'DCR'. This measurement will almost always be less than the driver's nominal impedance. Consumers sometimes get concerned the Re is less than the published impedance and fear that amplifiers will be overloaded. Due to the fact that the inductance of a speaker rises with a rise in frequency, it is unlikely that the amplifier will often see the DC resistance as its load.

Le   This is the voice coil inductance measured in millihenries (mH). The industry standard is to measure inductance at 1,000 Hz. As frequencies get higher there will be a rise in impedance above Re. This is because the voice coil is acting as an inductor. Consequently, the impedance of a speaker is not a fixed resistance, but can be represented as a curve that changes as the input frequency changes. Maximum impedance (Zmax) occurs at Fs.

Q Parameters   Qms, Qes, and Qts are measurements related to the control of a transducer's suspension when it reaches the resonant frequency (Fs). The suspension must prevent any lateral motion that might allow the voice coil and pole to touch (this would destroy the loudspeaker). The suspension must also act like a shock absorber. Qms is a measurement of the control coming from the speaker's mechanical suspension system (the surround and spider). View these components like springs. Qes is a measurement of the control coming from the speaker's electrical suspension system (the voice coil and magnet). Opposing forces from the mechanical and electrical suspensions act to absorb shock. Qts is called the 'Total Q' of the driver and is derived from an equation where Qes is multiplied by Qms and the result is divided by the sum of the same.

As a general guideline, Qts of 0.4 or below indicates a transducer well suited to a vented enclosure. Qts between 0.4 and 0.7 indicates suitability for a sealed enclosure. Qts of 0.7 or above indicates suitability for free-air or infinite baffle applications. However, there are exceptions! The Eminence Kilomax 18 has a Qts of 0.56. This suggests a sealed enclosure, but in reality it works extremely well in a ported enclosure.

Vas/Cms   Vas represents the volume of air that when compressed to one cubic meter exerts the same force as the compliance (Cms) of the suspension in a particular speaker. Vas is one of the trickiest parameters to measure because air pressure changes relative to humidity and temperature — a precisely controlled lab environment is essential. Cms is measured in meters per Newton. Cms is the force exerted by the mechanical suspension of the speaker. It is simply a measurement of its stiffness. Considering stiffness (Cms), in conjunction with the Q parameters gives rise to the kind of subjective decisions made by car manufacturers when tuning cars between comfort to carry the president and precision to go racing. Think of the peaks and valleys of audio signals like a road surface then consider that the ideal speaker suspension is like car

suspension that can traverse the rockiest terrain with race-car precision and sensitivity at the speed of a fighter plane. It's quite a challenge because focusing on any one discipline tends to have a detrimental effect on the others.

Vd   This parameter is the Peak Diaphragm Displacement Volume — in other words the volume of air the cone will move. It is calculated by multipying Xmax (Voice Coil Overhang of the driver) by Sd (Surface area of the cone). Vd is noted in cc. The highest Vd figure is desirable for a sub-bass transducer.

BL   Expressed in Tesla meters, this is a measurement of the motor strength of a speaker. Think of this as how good a weightlifter the transducer is. A measured mass is applied to the cone forcing it back while the current required for the motor to force the mass back is measured. The formula is mass in grams divided by the current in amperes. A high BL figure indicates a very strong transducer that moves the cone with authority!

Mms   This parameter is the combination of the weight of the cone assembly plus the 'driver radiation mass load'. The weight of the cone assembly is easy: it's just the sum of the weight of the cone assembly components. The driver radiation mass load is the confusing part. In simple terminology, it is the weight of the air (the amount calculated in Vd) that the cone will have to push.

Rms   This parameter represents the mechanical resistance of a driver's suspension losses. It is a measurement of the absorption qualities of the speaker suspension and is stated in N*sec/m.

EBP   This measurement is calculated by dividing Fs by Qes. The EBP figure is used in many enclosure design formulas to determine if a speaker is more suitable for a closed or vented design. An EBP close to 100 usually indicates a speaker that is best suited for a vented enclosure. On the contrary, an EBP closer to 50 usually indicates a speaker best suited for a closed box design. This is merely a starting point. Many well-designed systems have violated this rule of thumb! Qts should also be considered.

Xmax/Xmech   Short for Maximum Linear Excursion. Speaker output becomes non-linear when the voice coil begins to leave the magnetic gap. Although suspensions can create non-linearity in output, the point at which the number of turns in the gap (see BL) begins to decrease is when distortion starts to increase. Eminence has historically been very conservative with this measurement and indicated only the voice coil overhang (Xmax: Voice coil height minus top plate thickness, divided by 2). Xmech is expressed by Eminence as the lowest of four potential failure condition measurements times 2: Spider crashing on top plate; Voice coil bottoming on back plate; Voice coil coming out of gap above core; Physical limitation of cone. Take the lowest of these measurements then multiply it by two. This gives a distance that describes the maximum mechanical movement of the cone.

Sd   This is the actual surface area of the cone, normally given in square cm.

Zmax   This parameter represents the speaker's impedance at resonance.

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