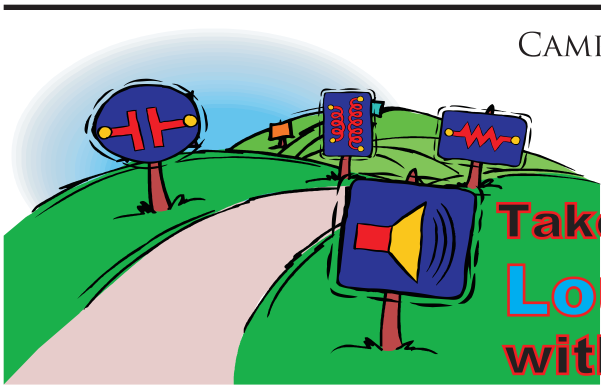
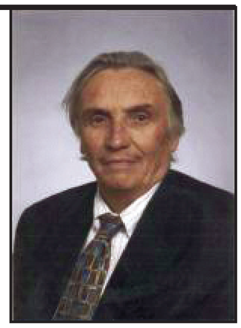
CAMPBELL'S CORNER - BY DICK CAMPBELL



Take a walk in Loudspeaker Park with me - Part 2



Getting ready for the box requires some understanding of the goals: good time accuracy, uniform response, adequate low frequency performance, correct integration with the rest of the loudspeaker system.

Assuming the box is sealed, it becomes an air spring loading a back of the driver. In addition we find that the air spring of the box is not the same as the air spring in, say a bicycle pump, which heats up because the pumping action is so slow that the heat of compression can move to the sidewalls of the pump and warm your hand.

But at audio frequencies, the wave cycle is so fast that heat does not move appreciably. The thermal diffusion speed in air is ~ 1.5m/sec (physicists will jump all over me for saying that!). If the heat does not transfer between air particles, then that retained energy simple adds to the spring constant. An 'acoustic' air spring is 1.4 times greater than the bicycle pump spring, a factor called γ in acoustics. See this link regarding isentropic expansion for a more complete explanation.

What does Q mean in terms of response? The classic diagram is Fig. 8.12 in Beranek "Acoustics", reproduced here as Fig. 5. The X-axis is frequency fraction relative to resonance.

Resonant peaks cause 'ringing'. If the system is driven by an impulse, the driver keeps wiggling at the resonant frequency for a short time afterward. This is not good for accurate reproduction of the drive signal. The resonance peak has to be pulled down to where the time-domain reproduction is accurate (meaning inaudible errors).

Although a Q target is nice, it must be achieved for the finished product—in this instance when the driver is installed in a sealed box. What follows may or may not be a good design choice, but it's a good example of the calculations.

Note that all of the acoustic volume velocity passes through the box. A sealed box acts as an additional spring, **Cab**, adding to the system compliance. The box also has resistance, **Rab** (stuffing loss) and a bit of mass, **Mab** (some air moves to pressurize it). Figure 2 shows the new equivalent circuit after adding the box, however in mechanical units, properly inserted into a mechanical circuit. Figure 3 is the same circuit in acoustic units.

The compliance (air spring) of the sealed box shifts the combined resonance to a higher frequency. Why higher? Because the two capacitors are in series. Resistors in series add, inductors in series add, but capacitors in series must be calculated using product over the sum (like resistors in parallel).

How do we get the values for **Cmb, Mmb and Rmb**? Again, from Beranek (and other books on loudspeaker design) we see that **Cmb** relates to the volume of the box which is, of course an acoustic measurement. We are really calculating **Cab** and transforming it to **Cmb** in Fig. 2. This figure has five so-transformed acoustic components.

Why not use an acoustical equivalent circuit to begin with? No problem – just have to deal correctly with **Sd²** for the non-acoustical components. The radiation becomes **Rar+jXar**, and the box has **Rab, Mab** and **Cab**. These are straightforward to calculate or to take from graphs.

Figure 3 is an acoustic view of Fig. 2 but with all terms transformed into acoustic units.

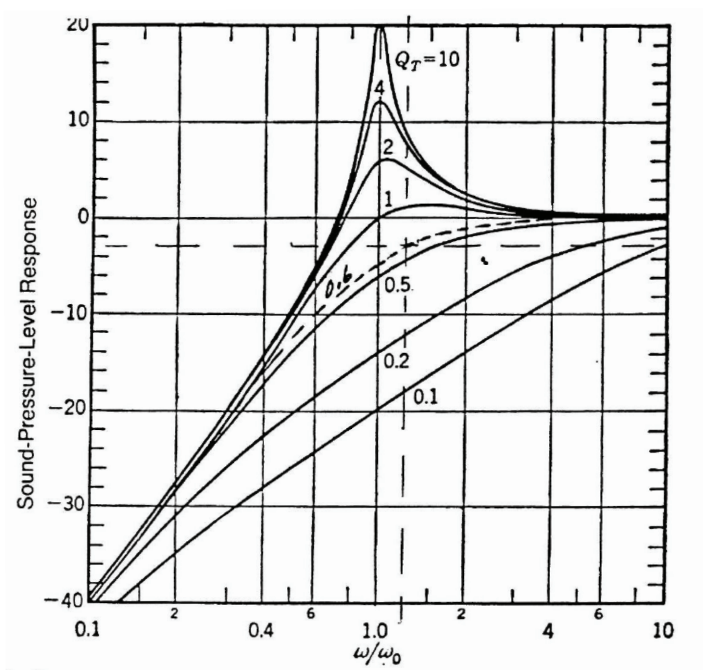


*Figure 1 - The peak SPL of a Q-curve is 10*log(Q) at resonance. Q control is important to achieve the best possible time-domain response. The dashed line, Q ~0.6, is nearly ideal. However, Q=1 might be acceptable under non-critical listening conditions and has a low-frequency -3dB point at ~60Hz. Note that there is a penalty to pay in low-frequency response between Q=1 and Q=0.6. The data from the MISCO driver (free air) ranges from 2.2 (SPL bump~3.4dB) to 0.36 (SPL low frequency cutoff four times free–air resonance, 280Hz)!*

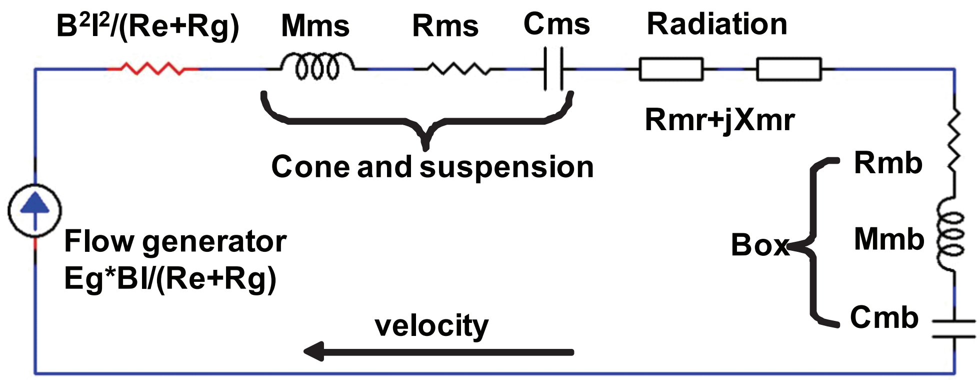


Figure 2. Mechanical equivalent circuit for sealed-box loudspeaker system.

But wait! All we did was divide each non-acoustic passive element by **Sd²**, except the compliance, **Cms**. Why is that one *multiplied* by **Sd²**?

Because the *reactance* at any given frequency is what this analysis is all about. The inductive reactance (kinetic energy storage) of the Mms component is ω**Mms**. Resistance is just resistance. But capacitive reactance (potential energy storage) is 1/ω**Cms**. Therefore the acoustic transform of **Cms** to **Cas** requires a product term. Compliance is in m/N. For all acoustical reactance terms to agree we must have N-s/m⁵ for units. Inverting compliance (called 'stiffness') and multiplying **Cms** by **Sd²** provides the required N-s/m⁵. When in doubt, always analyze the units of every term, a technique called "dimensional analysis."

Rab is the acoustic resistance of the box. This can be estimated by knowing the quantity of stuffing material and its flow rate. It's better to leave that to the end because it contributes a certain amount of Q control but we don't know how much is needed yet.

Cab is the acoustic compliance of the box and is expressed as box-volume V/(γ*P_0), where γ = 1.4 and P_0 is 10^5 N/m² for the resting pressure of air at standard conditions. The units are m⁵/N and when the acoustic reactance is computed as 1/(ω***Cab**) the units are correct.

Mab is taken from an equation having to do with the ratio of box frontal area to the area of the driver and is given as B*ρ_0/π*a where a is the driver radius, γ = 1.4, ρ_0 =1.18 and B can range from 0.3 for 1:1 area ratio (example: driver at the end of a tube) to 0.85 for a huge box. Maybe 0.5 would be okay. With a radius of 0.047m, **Mab** computes to ~3.90 Kg/m⁴. Compare his to **Ma1** which is 0.23/a = 4.9 Kg/M⁴. So the box mass loading on the rear side of the driver is nearly equal to the radiation mass loading on the front side.

What size box? That is the next question to be answered. Since we know how the total compliance will be calculated it is possible to reduce the calculation to a rather simple equation (*Beranek, chp.8*):

$$\frac{f_B}{f_0} = \sqrt{0.87\left(1+\frac{Cas}{Cab}\right)}$$

Here f_0 = 70Hz and **Cas** = 6.08E-08 m⁵/N. It appears the new resonance frequency with the sealed enclosure will have to be chosen before **Cab** and the box volume can be calculated. If this loudspeaker is to be used with a sub-woofer, then 110Hz might be a good target for f_B. Knowing the target frequency ratio, 110/70 = 1.57, and **Cas,** it is now possible to calculate **Cab**. From Cab*γ*P_0 = ~4.6 liters, or a cube 17cm per side, like a small bookshelf.

What's the system Q? The radian frequency of the sealed box resonance is now 2*π*110 = 690.8 /s. The total acoustic mass M_A = **Mms/Sd²** +**Ma1**+**Mab** = 82.3+4.79+3.8 = 90.89 Kg/m⁴. The total resistance, R_A, has not changed appreciably at 1.10E5 acoustic ohms. The Q therefore is 690.8*90.89/1.10E5 = 0.57. Clearly, more R_A is not needed. In fact, this Q is nearly ideal. Unfortunately, this means that the advertised -3dB point is shifted up by ~1.2 to ~130Hz.

What have we learned? How the driver parameters together with the design target give us a first cut at the size of the box. We also discussed mechanical and acoustical parameters, how to convert between them, and how they affect frequency response.

In Part 3 we will see how to use this electrical analog to predict loudspeaker performance. *dc*

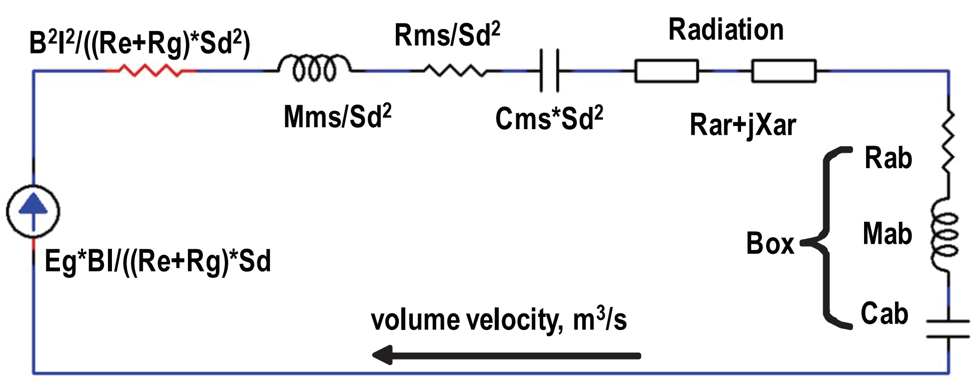


*Figure 3. Sealed box equivalent circuit expressed in acoustic units. At very low frequencies the **Rar** term, radiation resistance, can be nearly zero, and **Xar** is the air mass reactance.*