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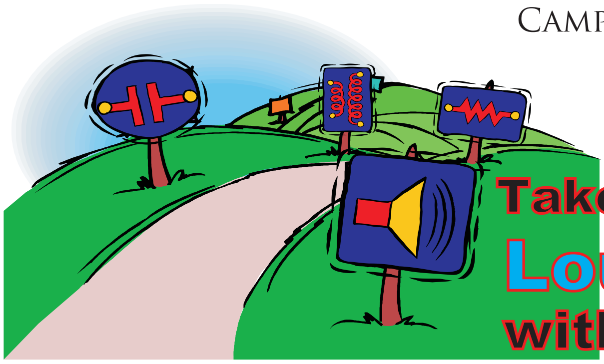
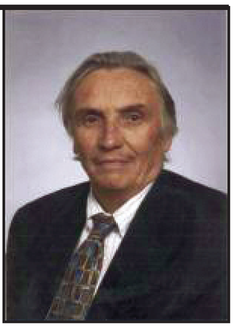
CAMPBELL'S CORNER - BY DICK CAMPBELL





Take a walk in Loudspeaker Park with me - Part 1

Too much series resistance in loudspeaker wiring pops up from time to time. Sometimes long runs are unavoidable, so the question of what wire size must be answered. But aside from the rather obvious loss of sensitivity, meaning increased line loss, what else happens?

Conventional loudspeakers have extremely low impedance, perhaps four to eight ohms, and if a similar resistance exists in the wiring then the sensitivity drops 6 dB. One might look at powered units but frequently power is not available at the location of the loudspeaker. Using 70 V lines and transformers is another choice. If copper wire is used, then the following table applies:

AWG	Dia. Inch	Dia. mm	Ohms/km	Ohms/kft	Feet/Ohm
10	0.1019	2.588	3.277	0.9989	1001.10
12	0.0808	2.053	5.211	1.588	629.72
14	0.0641	1.628	8.286	2.525	396.04
16	0.0508	1.291	13.17	4.016	249.00
18	0.0403	1.024	20.95	6.385	156.62
20	0.0320	0.812	33.31	10.150	98.52

Remembering that what goes down must come back, it's the loop resistance that counts. So looking at the entry for #18 wire, about 78 feet would be one ohm of loop resistance resulting in ~1dB of loss in SPL for an 8 ohm load.

All is well and good except that a loudspeaker load impedance is not constant with frequency. Between driver parameters and passive crossovers there can be significant variability. It follows that if additional resistance is placed between the power amplifier and the loudspeaker, the sound level will change and the frequency response is likely to change.

We will model a small closed-box mid-woofer using AkAbak-TM and then vary the external resistance while estimating the SPL as a function of frequency. The AkAbak script describes the driver constants, and then it places free-space radiation at the front and an enclosure at the rear. This is a very nice 4.5 in full-range loudspeaker from MISCO, one of the leading production driver manufacturers in the USA. This design could be a small satellite loudspeaker.

But first, the fundamentals

The MISCO driver has a mechanical resonance at ~70 Hz in free air, caused by the moving mass of the driver talking to the spring that holds it all together. The driver really moves a lot at resonance: the voice coil is moving within the magnetic field thus acting as a generator. Think of this as the driver acting as a microphone. Trouble is, the voltage generated this way, called 'back EMF', is opposite to the voltage driving the unit. So we leave the speaker terminals open, and poke the driver diaphragm – a 'finger' impulse. Lo, it wiggles quite a bit at 70 Hz. Next experiment: put a short circuit on the driver terminals and lo, it hardly wiggles at all. The resonance is highly damped because the back-EMF now has to supply lots of current to the short—limited only by the dc resistance of the voice coil—and it can't. Probably you have heard the term for this - 'dynamic braking' - used in locomotives heading down hill for example. The dynamic braking in the loudspeaker system reduces the resonant peak.

The total resistance in the circuit determines the net damping. This includes the resistive parts of the voice-coil and crossover, the losses in the driver mechanical parts, the losses in any enclosure (like stuffing), the dynamic braking and the radiation resistance. Of these usually the dynamic braking is most significant part and the radiation resistance the least part.

Modeling the dynamic braking is done by equating the rise in the motion of the voice coil to a variable resistance in series with the coil dc resistance. Remember that if we are building an equivalent circuit of a complete loudspeaker, the electrical or acoustic or mechanical parameters must be transformed to equivalents in a single domain of your choice. If you like to work with mechanical units then the acoustic side and the electrical side must be expressed in mechanical terms. We are ahead of ourselves - time to simplify!

Take a walk in Loudspeaker Park with me

We stroll into the electrical terminals and find resistance, capacitance and inductance and we have to use current and voltage to describe the foliage. We walk through the voice coil and the magnet and we find mechanical resistance, compliance and mass, and we have to use force and velocity. Then we walk through the cone and we have to look both ways—we find acoustic radiation impedance on one side and, perhaps, acoustic compliance, inductance and resistance on the other side. Here we use acoustic terms like pressure and particle velocity.

Three different sections of the park: different dirt, different grass, different trees and different means of transport. Three domains are all joined together by a single path. The path conducts energy. What goes in must come out, minus the losses. The word 'domain' is a good one for mathematical considerations. Energy is conserved as it passes through the three domains—electrical, mechanical, and acoustical. Each transition requires a transform equation in order to make a complete math model.

Transforms of this type are bi-lateral–just like electrical transformers can be used backward - so exchanging mechanical and electrical is okay as long as we use transformer theory. In the case of the voice coil, its velocity (equivalent to 'secondary' voltage on the load side) generates a voltage in the 'primary' (the drive side).

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The presence of this voltage, the back EMF, causes a current to flow in a direction opposite to the driving current. Same drive voltage, lower drive current, but proportional to the voice coil velocity. Sound like higher impedance to me when it happens! This additional impedance is frequently called ‘motional impedance’.

If the goal is to construct an equivalent circuit model, then it would be useful to get rid of the transformers as a circuit element. In the loudspeaker circuit we have two transformers hooked together: first the electrical to mechanical, then the mechanical to acoustical. Can we just join them together somehow?

Oops—we have a problem

The first transformer we studied, electrical to mechanical, transforms current to force. The force is flowing in the loop and the velocity is driving it. But the transformer we want to connect to complete the circuit has, at its primary, velocity flowing and force driving. Oh oh.

Setting up the solution

Here we see the electrical side being ‘inverted’. Instead of a voltage source, there is a current source driving. This transforms to force, then ultimately to pressure. Maybe now, by using transformer theory, we can eliminate the transformers and be left only with mechanical circuit elements.

Remembering transformer theory

Voltages and currents are transformed by the turns ratio. Impedance is transformed by the turns ratio squared. We must decide which set of units will be used for the entire schematic. So let’s stay with mechanical units and derive values for the new schematic without transformers. But first we must create a nomenclature to keep straight which domain we are representing in the variables. **Zar** means ‘impedance, acoustic units, radiation’. **Zmr** means ‘impedance, mechanical units, radiation’ (transformed, of course).

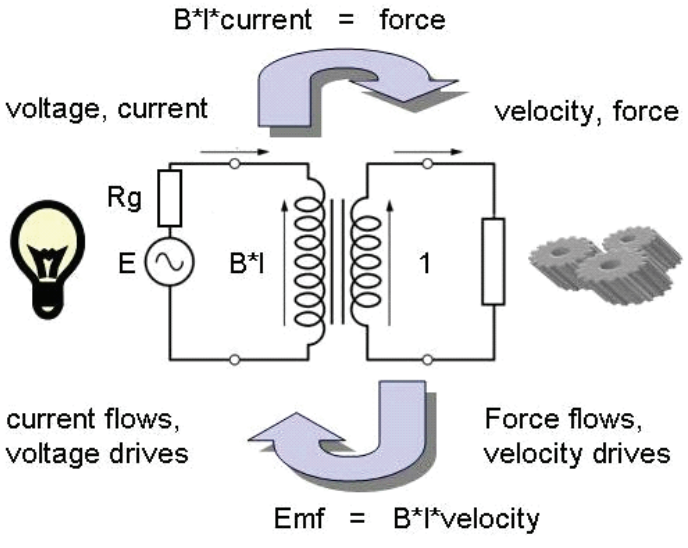

*Figure 1 - The first "transformer" is electrical to mechanical. The modeling device used is an electrical transformer with a winding ratio of B*l (primary) to 1 (secondary). Why? Because force equals magnetic field strength (B) times the length of the wire in the field (l) times the electrical current flow (good old Faraday).*

Let’s first get rid of the second transformer. **Sd** to **1**. **Zar**, the radiation impedance, is transformed by multiplying by **Sd**^{2}, e.g. **Zmr=Zar*Sd**^{2}**.** This element can then be directly connected to the mechanical domain.

The first transformer is bit more of a problem. The electrical current is multiplied by the **B*l** product to get force because force ‘driving’ is now our norm in this schematic.

Therefore the electrical circuit has to include a current generator with parallel Norton impedance connected to the primary side and must he divided by **(Bl)**^{2}. For example, **Rem**=**Re**/**(Bl)**^{2} meaning the voice coil Norton resistance is transformed to its mechanical equivalent. Same with the voice coil inductance, **Le** and the generator resistance, **Rg**.

Applying circuit theory

The electrical side is a current generator, not a voltage generator. Therefore the electrical elements that we wish to reflect into the mechanical domain have to be inverted. This is the same transform as a Thevenin to Norton circuit inversion. Now we can model the entire circuit as one mechanical velocity loop (Figure 4).

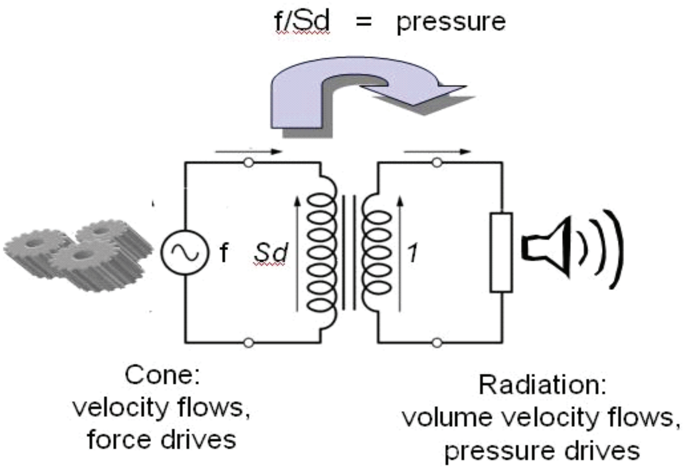

Figure 2 - The second transformer is mechanical to acoustical. This one is a bit simpler in that the transform describes the cone on one side and the radiated field on the other. The cone moves and pressurizes the air causing acoustic radiation.

The transform here is simply cone area, since the force, f, is the primary driving quantity an pressure appears at the secondary.

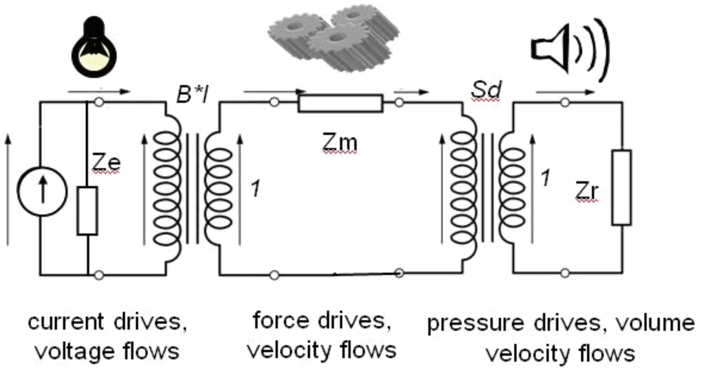

Figure 3 - Setting up the solution

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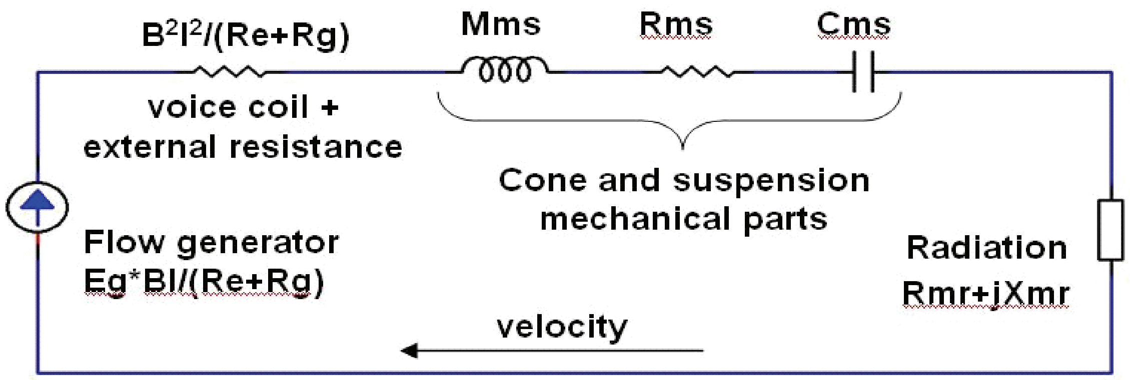

Mmd = mass of the diaphragm	3.99E-03 Kg [N-s^2/m]
Mm1 = mass of air layer (two sides)	2.4E-04 Kg
Rms = losses in the suspension	0.371 mechanical ohms [N-s/m]
Cms = suspension compliance	1.16E-03 m/N
Zar = radiation impedance, Rar + jXar	52.9+j23.8E-02 acoustic ohms [N-s/m^5]
Bl = Magnetic force factor	6.1 T-m
Sd = Diaphragm area	7.24E-03 m^2
f0 = free-air resonance	70 Hz
Re = Voice coil DC resistance	6.9 ohms

Figure 4 - These are the free-air mechanical quantities partially from the MISCO KC42F-8A data sheet.

Back to Loudspeaker Park

You are standing in the mechanical middle. Look to your right and you see the acoustic part but through the prism of diaphragm area squared. Look to your left and you see the electrical source but through the prism of an equivalent current generator.

Eg is the voltage generator that establishes the current source. Let's assume the generator resistance, **Rg** = 0 ohms. Therefore the velocity flowing in the loop is inversely proportional to Re and the current flowing is driven be **Eg*Bl**. Send in 1 volt and you get 0.146 m/s in the loop all the time.

There will be a resonance, of course, and we know it to be ~70Hz. How important the resonance is depends upon the damping in the loop, namely the total resistance. The relative narrowness of the resonant peak is represented by 'Q'. To actually measure Q, we can record the peak impedance and frequency, then follow the curve on each side of peak to 0.707 of the peak value, and measure the frequency at those points. Then we take the difference between these points in Hz and divide it into the center frequency to get Q.

In electrical circuit terms, Q = ωM/R and in the case of our speaker model, equals ω*(Mmd+Mm1)/Rloop. It is convenient to have a model were all the velocity flows in one loop, because the Rloop is simply all the R's added together (remembering **Rg**=0), and in free air, the **Rmr** is doubled – both sides radiating into a real load. Note that it is 1000 times lower than any other resistive term in the loop, so it too may be ignored.

Summing the mechanical mass reactance gives ωM = ω(Mmd + Mm1) which is

~70*2*π / s * 0.0047N-s^2/m = ~2.05 N-s/m

For the mechanical components only, the Q is called Qms, which calculates to 5.5. This includes the diaphragm air layer mass. This agrees with the advertised value. This simulates open terminals.

For shorted terminals, where **Re** comes into play increasing the damping component, the Q is called Qts where the total mechanical resistance is called R_M and is 5.77 N-s/m. It's easy to see that **(Bl)^2** is in control because Qts drops to 0.355.

$$\text{Qts} = \omega \frac{\text{Mmd} + \text{Mm1}}{\text{Rm}}$$

Using a different magnet or changing the length of the voice-coil wire or adding more generator resistance can have a profound effect.

What have we learned?

The driver free-air mechanical parameters are listed as extracted using MLSSA, for example. Then a mechanical equivalent circuit was created. This started out using two transformers to model the domain changes, but these were substituted by emulating transformer theory and putting the acoustical and electrical parameters into the mechanical domain. Now we have a flow loop that can be analyzed using circuit theory. Extra resistance on the electrical side means higher Q because the term Rg is in the denominator of the equation.

In Part 2 I will discuss what happens when this driver is mounted in an enclosure. *dc*