Crossover Modeling Methods for MEH Designs

By Martin J King
MJKing57@aol.com

June 23, 2026

- Introduction
- MEH Circuit Models w/ an Active Crossover
- MEH Acoustic KVL Equations w/ an Active Crossover
- MEH Circuit Models w/ a Passive Crossover
  - What's in the Box?
  - Thevenin's Theorem and Sample Passive Crossover Model
- MEH Acoustic KVL Equations w/ a Passive Crossover
- Summary

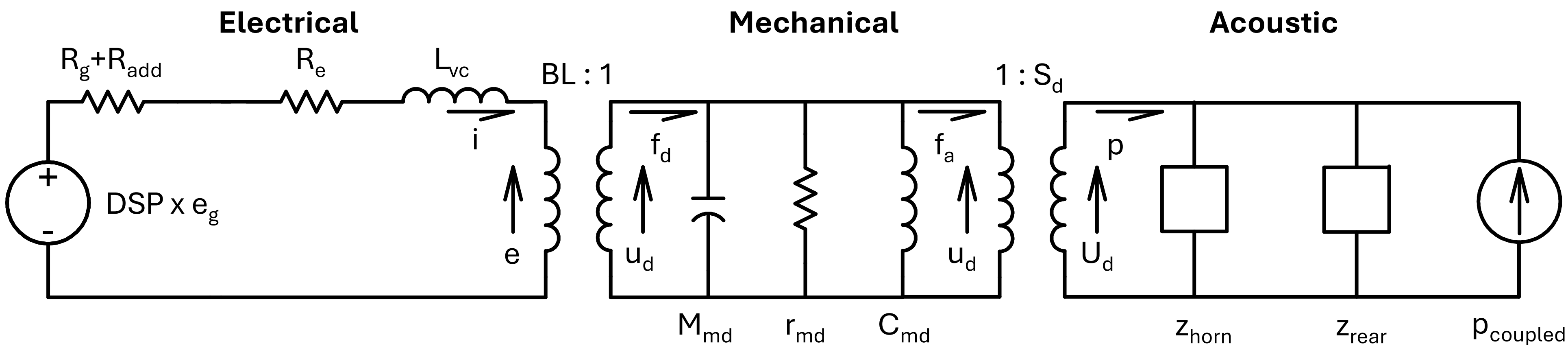
Introduction

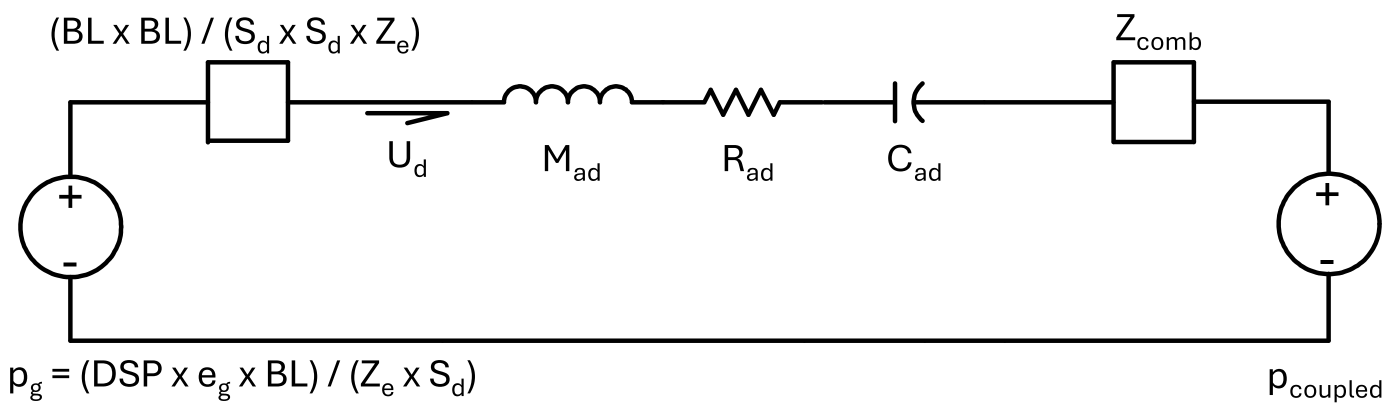
The first presentation in this series, "Multi Entry Horn Modeling Methods", provided a quick overview of the new MEH MathCad worksheets and showed a sample problem that demonstrated a few of the potential design trade-offs. One topic that was presented, but not really explored or explained, was the analysis method for active and passive crossovers used in these more complex equivalent circuit models.

Equivalent electrical and acoustic circuit models are the backbone of most speaker design simulations. The complete circuits are composed of electrical, mechanical, and acoustic elements linked together through two transformers representing the boundary/transition between each portion of the circuit. Typically, equivalent circuit models are manipulated into either a completely electrical or a completely acoustic circuit by pulling individual elements through the transformers. This is a well know process that is demonstrated in texts (Beranek's acoustics texts are where I learned the fundamentals) and papers (Thiele and Small papers are excellent complete references) so it will not be repeated.

The added complexity in the MEH speaker system is the coupling between the drivers through the horn's air volume. As shown in the first presentation, for a three way MEH you end up with three coupled equations with three unknowns that all have magnitude and phase (real and imaginary components), Adding a crossover to the equivalent circuit model can be simple for an active system but becomes very messy for a completely passive system (crossover with additional passive filters).

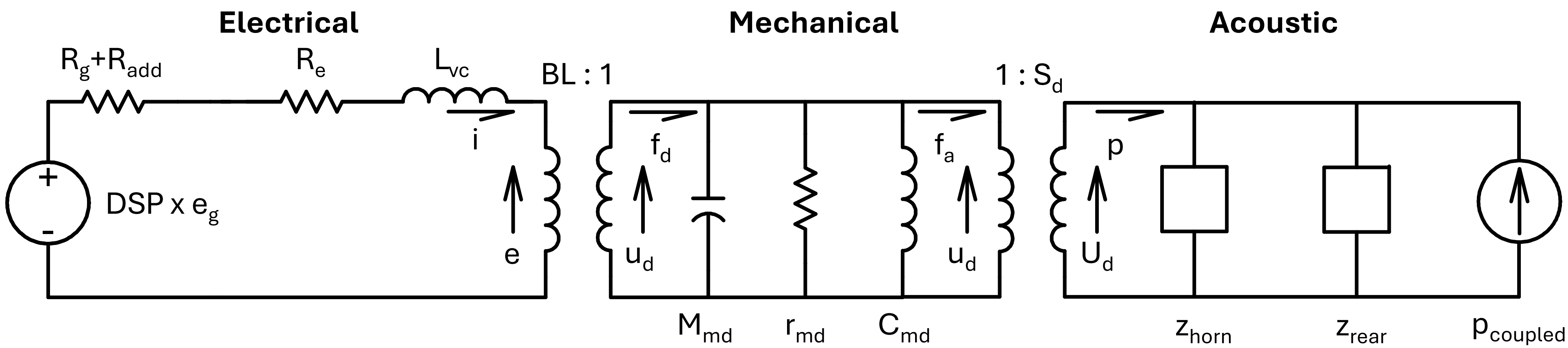
MEH Circuit Models w/ an Active Crossover





DSP = active crossover
$Z_e = R_g + R_{add} + R_e + j\,\omega\, L_{vc}$
$Z_{comb} = Z_{horn} + Z_{rear}$

For the low frequency driver in a three-way MEH
$U_d = U_{d\_low}$
$p_{coupled} = Z_{low\_high} \times U_{d\_high} + Z_{low\_mid} \times U_{d\_mid}$

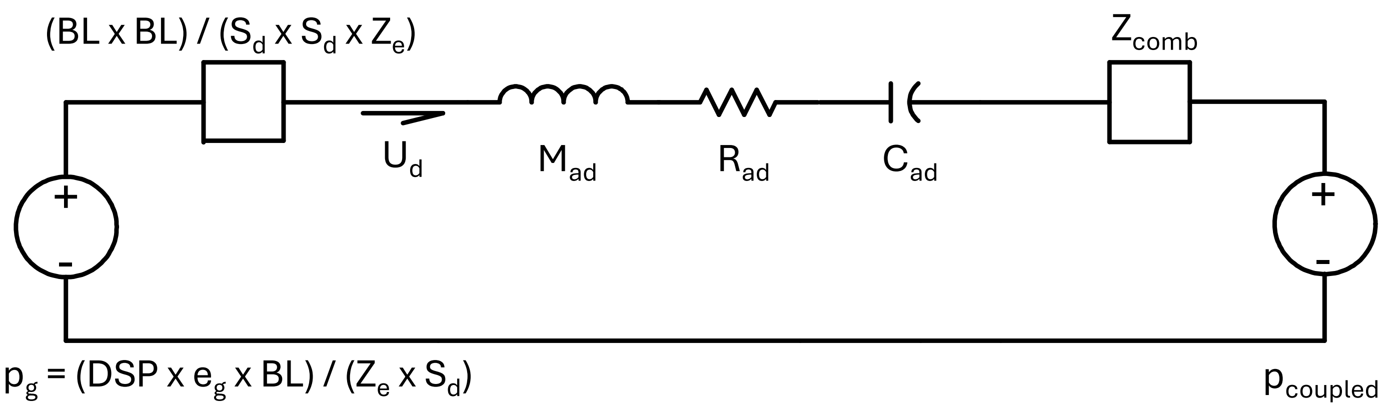


The complete equivalent circuit model, the upper plot in the previous slide, is repeated above. The only place the DSP crossover enters the model is at the voltage source on the far left. Each of the three drivers is modeled with this circuit configuration and coupled by the current source on the far right. Voltages are denoted by the complete arrows across circuit elements while currents are shown as one-sided arrows flowing between circuit elements.

To simplify the circuit Kirchhoff's voltage and current laws along with Thevenin's and Norton's theorems were applied. These methods can be found in any undergraduate AC and DC electrical circuits textbook. Wikipedia is also a great quick reference for definitions of these laws and theorems.

After manipulating the circuit elements, pulling them all over to the acoustical side of the complete circuit, the reduced impedance analogy acoustic circuit is derived and shown below. You can trace the individual circuit elements shown on the previous slide into this simplified circuit. Notice that all the circuit elements are now in series, so a single application of Kirchhoff's voltage law was used to derive the equation to be solved. This was repeated for each driver in the three-way MEH speaker system. The final set of coupled equations for the active crossover design are shown on the following slide.

The active crossover case was fairly straight forward and very similar to a single driver front loaded horn with the addition of the coupling impedances created by the other drivers in the MEH.



DSP = active crossover

$Z_e = R_g + R_{add} + R_e + j\ \omega\ L_{vc}$

$Z_{comb} = Z_{horn} + Z_{rear}$

For the low frequency driver in a three-way MEH

$U_d = U_{d\_low}$

$p_{coupled} = Z_{low\_high} \times U_{d\_high} + Z_{low\_mid} \times U_{d\_mid}$

MEH Acoustic KVL Equations w/ an Active Crossover

- Low Frequency Driver

$(DSP_{low} \times e_{g\_low} \times BL_{low}) / (Z_{e\_low} \times S_{d\_low}) – [(BL_{low} \times BL_{low}) / (S_{d\_low} \times S_{d\_low} \times Z_{e\_low}) + j\ \omega \times M_{ad\_low} + R_{ad\_low} + 1 / (j\ \omega \times C_{ad\_low})$
$+ Z_{comb\_low}] \times U_{d\_low} – (Z_{low\_high} \times U_{d\_high} + Z_{low\_mid} \times U_{d\_mid}) = 0$

- Mid Frequency Driver

$(DSP_{mid} \times e_{g\_mid} \times BL_{mid}) / (Z_{e\_mid} \times S_{d\_mid}) – [(BL_{mid} \times BL_{mid}) / (S_{d\_mid} \times S_{d\_mid} \times Z_{e\_mid}) + j\ \omega \times M_{ad\_mid} + R_{ad\_mid} + 1 / (j\ \omega \times C_{ad\_mid})$
$+ Z_{comb\_mid}] \times U_{d\_mid} – (Z_{mid\_high} \times U_{d\_high} + Z_{mid\_low} \times U_{d\_low}) = 0$

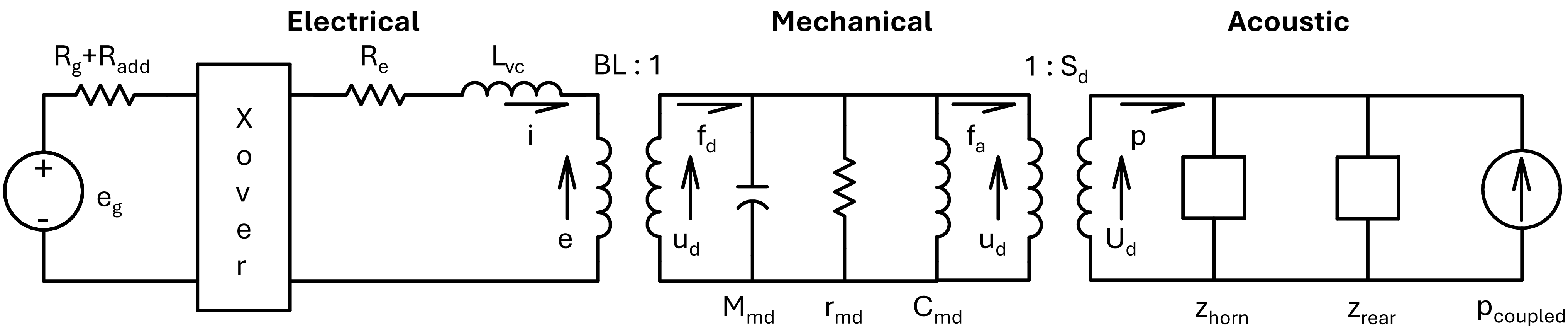
- High Frequency Driver

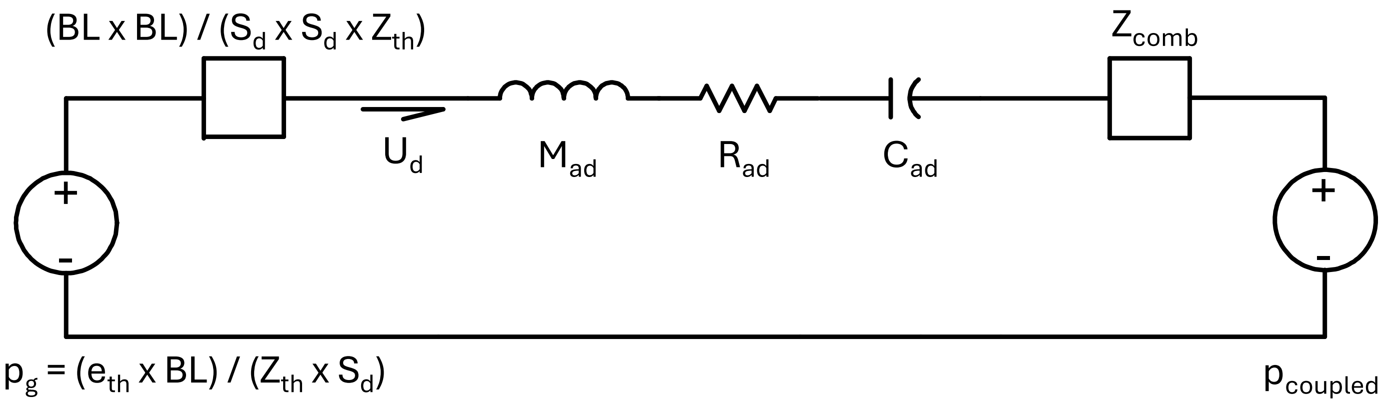
$(DSP_{high} \times e_{g\ \_high} \times BL_{high}) / (Z_{e\_high} \times S_{d\_high}) – [(BL_{high} \times BL_{high}) / (S_{d\_high} \times S_{d\_high} \times Z_{e\_high}) + j\ \omega \times M_{ad\_high} + R_{ad\_high} + 1 / (j\ \omega \times C_{ad\_high})$
$+ Z_{comb\_high}] \times U_{d\_high} – (Z_{high\_mid} \times U_{d\_mid} + Z_{high\_low} \times U_{d\_low\backslash}) = 0$

- Three Equations with Three Unknowns

U_{d_low}, U_{d_mid}, and U_{d_high} which all have magnitude and phase and are functions of frequency

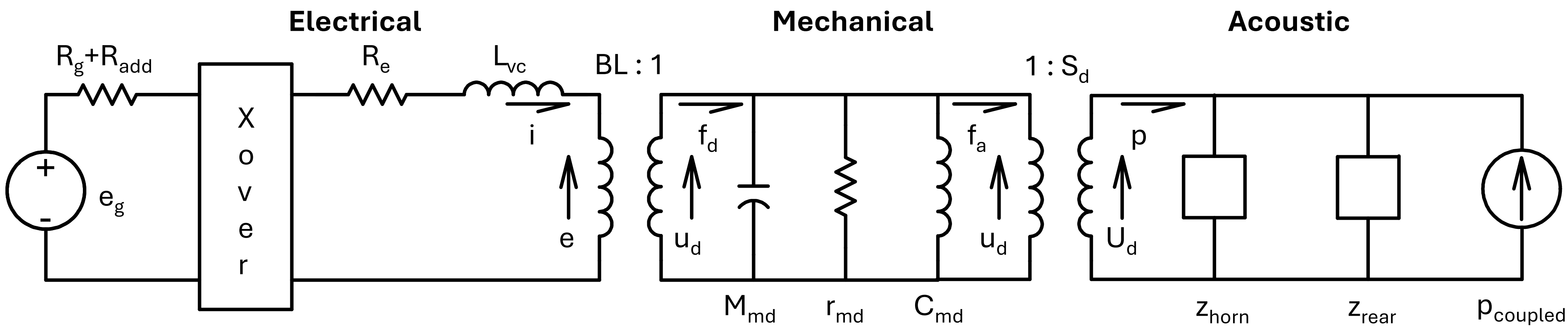
MEH Circuit Models w/ a Passive Crossover





e_{th} = Thevenin equivalent voltage source

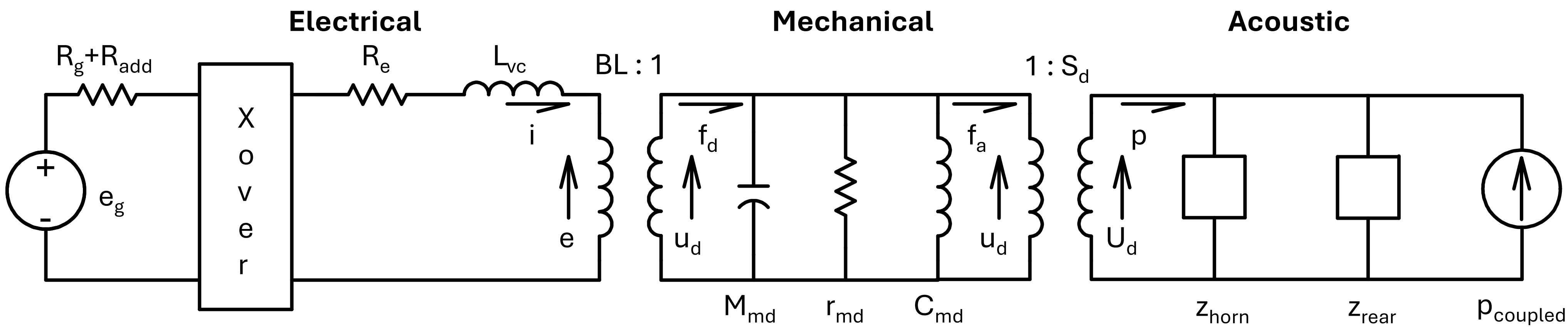
Z_{th} = Thevenin equivalent impedance



The complete equivalent circuit model, the upper plot in the previous slide, is repeated above. The use of a passive crossover and passive filters is depicted as a box between the amplifier and the driver terminals. Depending on the order of the crossover, and the number of passive filters being used to modify the electrical impedance of each driver, the circuit in the box can become very complicated.

The same Kirchhoff's voltage and current laws along with Thevenin's and Norton's theorems were used, with Thevenin's theorem becoming the game changer, for simplifying the circuits in the box.

What's in the Box?

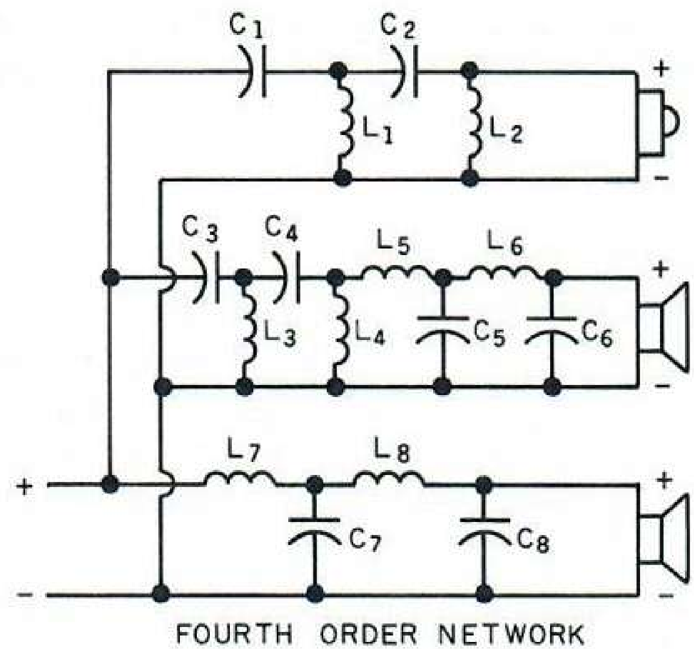


The box contains all the passive circuits used for a given driver in a MEH speaker design.

- Crossover
- Zobel
- Resonance Traps
- L-Pad
- Any other passive filter elements

Resolving these filters into something easy to calculate and then derive the speaker electrical impedance or SPL response can be a programming/mathematical nightmare. The next two slides show what was included in the box of the MEH models.

Three-Way Crossovers



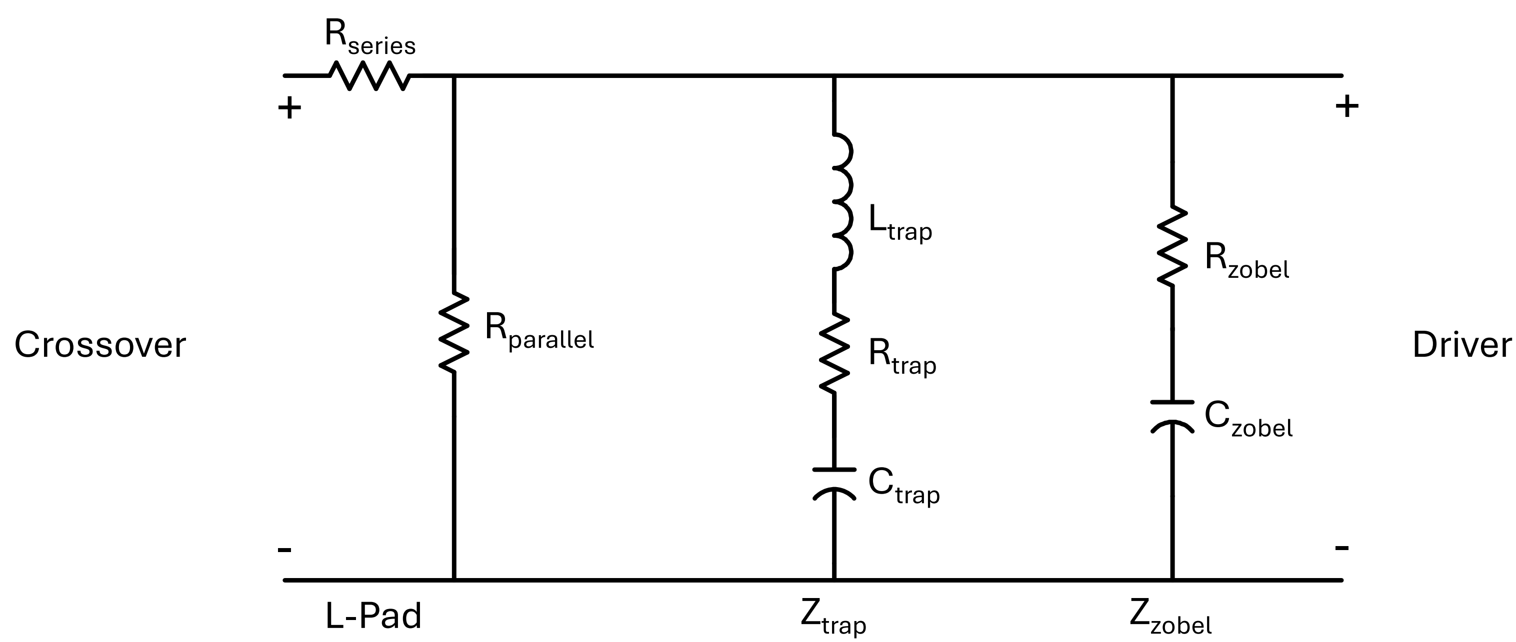
High Frequency Driver

Mid Frequency Driver

Low Frequency Driver

Lower Order Crossovers can be Simulated by Shorting or Opening Unused Circuit Elements

Compensation Networks



Additional Filters can be Inserted Between the Crossover and the Driver

Thevenin’s Theorem and Sample Passive Crossover Model

Calculating the Thévenin equivalent

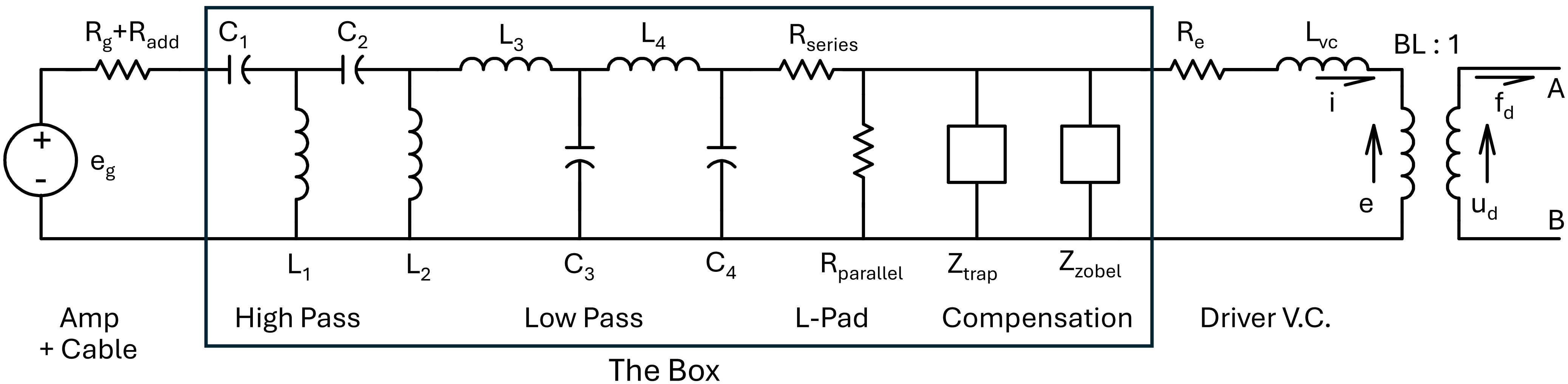
The Thévenin-equivalent circuit of a linear electrical circuit is a voltage source with voltage V_{th} in series with a resistance R_{th}.

The Thévenin-equivalent voltage V_{th} is the open-circuit voltage at the output terminals of the original circuit. When calculating a Thévenin-equivalent voltage, the voltage divider principle is often useful, by declaring one terminal to be V_{out} and the other terminal to be at the ground point.

The Thévenin-equivalent resistance R_{Th} is the resistance measured across points *A* and *B* "looking back" into the circuit. The resistance is measured after replacing all voltage- and current-sources with their internal resistances. That means an ideal voltage source is replaced with a short circuit, and an ideal current source is replaced with an open circuit. Resistance can then be calculated across the terminals using the formulae for series and parallel circuits. This method is valid only for circuits with independent sources. If there are dependent sources in the circuit, another method must be used such as connecting a test source across A and B and calculating the voltage across or current through the test source.

Reference : https://en.wikipedia.org/wiki/Th%C3%A9venin%27s_theorem

Complete Electrical Side for the Mid Driver of an MEH - This is What's in the Box



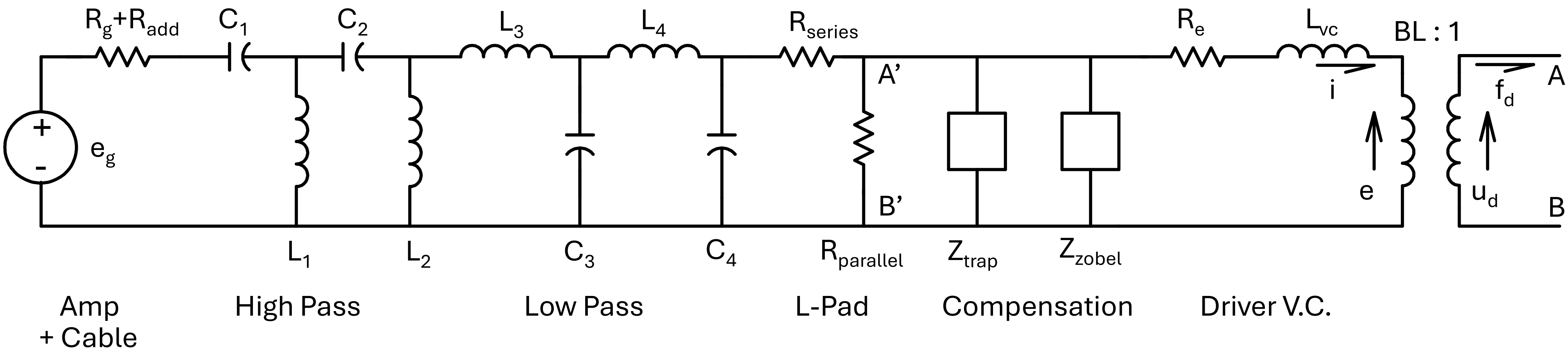
At the terminals A – B :

Open circuit : $f_d = i = 0$
$V_{oc} = u_d = e / BL$

Short circuit : $u_d = e = 0$
$I_{sc} = f_d = BL \times i$

$Z_{th} = V_{oc} / I_{sc}$

Z_{th} can also be calculated by replacing e_g with a short and then using series and parallel impedances to calculate the equivalent impedance from right to left.



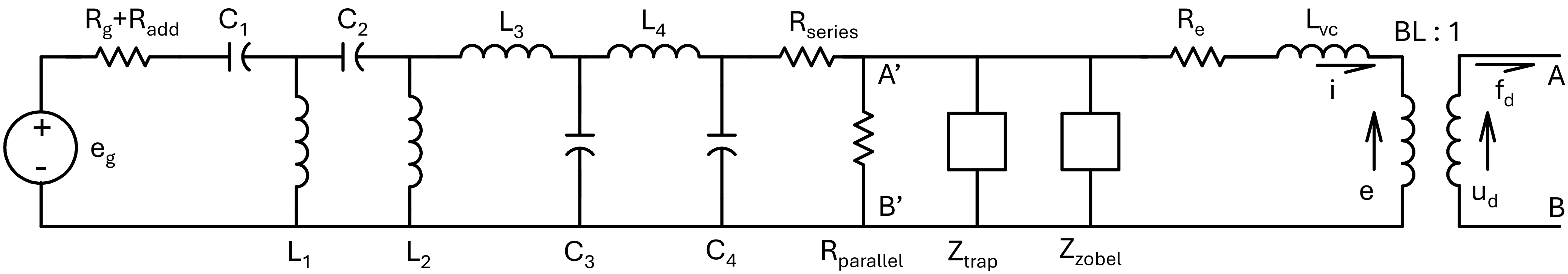
For the mid frequency driver in a three-way MEH design all the filter elements are active.

To calculate Z_{th}, replace e_g with a short and calculate the equivalent impedance of the electrical part of the model. Components in series are indicated by "+" and those in parallel are denoted by "||", this is shorthand for the calculation process.

$Z_{th} = R_e+L_{VC}+(Z_{zobel}||Z_{trap}||R_{parallel}) \; || \; [R_{series}+ C_4||(L_4+C_3||(L_3+L_2||(C_2+L_1||(C_1+R_g+R_{add}))))]$

To calculate $V_{th} = V_{oc}$, note that the voltage at A-B is the same as at A'-B' since i = 0. Use a series of voltage divisions to calculate the voltage across $R_{parallel}$.

$e_{th} = V_{oc} = e = e_g \times [L_1 / (R_g+R_{add}+C_1+L_1)] \times (L_2 / (C_2+L_2)] \times [C_3 / (L_3+C_3)] \times [C_4 / (L_4+C_4)] \times [R_{parallel} / (R_{series}+R_{parallel})]$



For the low frequency and high frequency drivers, the crossover splits into low and high pass filters acting on each driver respectively. Again, components in series are indicated by "+" and those in parallel are denoted by "||", this is shorthand for the calculation process.

$Z_{th\_low} = R_e+L_{VC}+(Z_{zobel}||Z_{trap}||R_{parallel}) \,||\, [R_{series}+ C_4||(L_4+C_3||(L_3+ R_g+R_{add}))]$ <---- since C_1, C_2, L_1, and L_2 are removed.

$Z_{th\_high} = R_e+L_{VC}+(Z_{zobel}||Z_{trap}||R_{parallel}) \,||\, [R_{series}+L_2||(C_2+L_1||(C_1+R_g+R_{add}))))]$ <---- since C_3, C_4, L_3, and L_4 are removed.

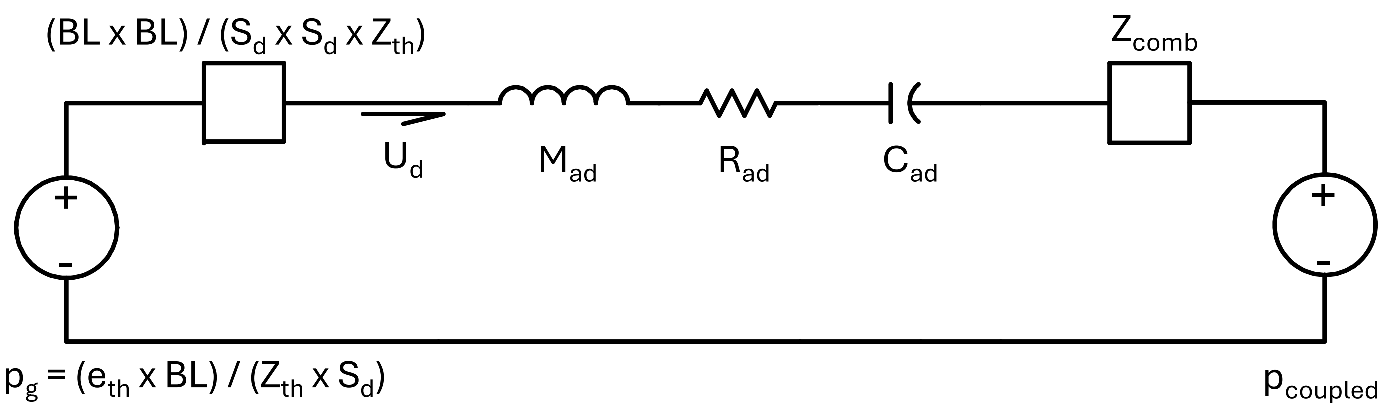
To calculate $V_{th} = V_{oc}$, note that the voltage at A-B is the same as at A'-B' since i = 0. Use a series of voltage divisions to calculate the voltage across $R_{parallel}$.

$e_{th\_low} = V_{oc} = e = e_g \times [C_3 / (R_g+R_{add}+ L_3+C_3)] \times [C_4 / (L_4+C_4)] \times [R_{parallel} / (R_{series}+R_{parallel})]$ same circuit elements removed.

$e_{th\_high} = V_{oc} = e = e_g \times [L_1 / (R_g+R_{add}+C_1+L_1)] \times (L_2 / (C_2+L_2)] \times [R_{parallel} / (R_{series}+R_{parallel})]$ same circuit elements removed.

To double check the Thevenin equivalent circuit modeling technique, a three-way TL design worksheet with an explicit solution for the passive crossover was converted to this newer method. Exercising the different order passive crossovers in the two worksheets produced identical results. The two methods checked.

The MEH passive crossover reduced acoustic impedance analogy circuit is very similar to the active crossover version of the MEH circuit shown on slide 6. Again notice that all the circuit elements are now in series, so a single application of Kirchhoff's voltage law was used to derive the equation to be solved. This was repeated for each driver in the three-way MEH speaker system. The final set of coupled equations for the passive crossover design are shown on the following slide.



e_{th} = Thevenin equivalent voltage source

Z_{th} = Thevenin equivalent impedance

MEH Acoustic KVL Equations w/ a Passive Crossover

- Low Frequency Driver

$(e_{th\_low} \times BL_{low}) / (Z_{th\_low} \times S_{d\_low}) – [(BL_{low} \times BL_{low}) / (S_{d\_low} \times S_{d\_low} \times Z_{th\_low}) + j\, \omega \times M_{ad\_low} + R_{ad\_low} + 1 / (j\, \omega \times C_{ad\_low})$
$+ Z_{comb\_low}] \times U_{d\_low} – (Z_{low\_high} \times U_{d\_high} + Z_{low\_mid} \times U_{d\_mid}) = 0$

- Mid Frequency Driver

$(e_{th\_mid} \times BL_{mid}) / (Z_{th\_mid} \times S_{d\_mid}) – [(BL_{mid} \times BL_{mid}) / (S_{d\_mid} \times S_{d\_mid} \times Z_{th\_mid}) + j\, \omega \times M_{ad\_mid} + R_{ad\_mid} + 1 / (j\, \omega \times C_{ad\_mid})$
$+ Z_{comb\_mid}] \times U_{d\_mid} – (Z_{mid\_high} \times U_{d\_high} + Z_{mid\_low} \times U_{d\_low}) = 0$

- High Frequency Driver

$(e_{th\_high} \times BL_{high}) / (Z_{th\_high} \times S_{d\_high}) – [(BL_{high} \times BL_{high}) / (S_{d\_high} \times S_{d\_high} \times Z_{th\_high}) + j\, \omega \times M_{ad\_high} + R_{ad\_high} + 1 / (j\, \omega \times C_{ad\_high})$
$+ Z_{comb\_high}] \times U_{d\_high} – (Z_{high\_mid} \times U_{d\_mid} + Z_{high\_low} \times U_{d\_low\backslash}) = 0$

- Three Equations with Three Unknowns

U_{d_low}, U_{d_mid}, and U_{d_high} which all have magnitude and phase and are functions of frequency

Summary

Being able to model active and passive crossovers in a MEH speaker system allows iterative simulations to achieve a final design before purchasing any hardware or building any enclosures. Having confidence in a design allows a single build followed my measurements and minor tweaking, a process that is both efficient and cost effective.

If the measurements match the simulation, then a complete understanding of how the system works has been achieved. With an understanding and a calibrated mathematical model more detailed analytic examinations of acoustic phenomenon happening inside the MEH speaker, that are not easily measured, can be performed. This allows intelligent design trade-offs to be explored without resorting to trial-and-error experimentation.

If predictions match measured results, then all the important variables have been captured by the model and optimization through further simulations is possible. Trial-and-error guesswork or intuitively driven changes are alternate paths forward, but it is not so easy to achieve an optimum result with either method.

Accurately modeling both active and passive crossovers, or a combination of the two, in an MEH simulation is a significant step forward in the MathCad worksheets for a subsequent DIY design and build.