Crossover Design with MATLAB: Tutorial

March 24, 2007

What today is all about

By now we've learned a bit about how speakers work and how sound waves interact; and we want to be able to design our own speaker system. So, it's time to put our knowledge to good use. We'll get acquainted with MATLAB - a powerful program for science and math - and use it to do the nasty computations involved with impedances. We can design filters that use resistors, inductors, and capacitors and use MATLAB to simulate their effects on actual speaker drivers. This way, we can experiment with lots of different drivers and filter circuits without actually having to build speakers. You'll first learn how the system works by simulating a simple 2-way speaker design, and then you'll be able to create crossovers to go with any combination of different woofers, midranges, and tweeters. I hope you have a good time.

Using MATLAB

On the MIT Server computing system at MIT, we have a program called MATLAB which can do lots of calculations very quickly, even with complex numbers (which describe, for example, both a signal amplitude and a phase shift). It also helps us make graphics to observe the results of our simulations. We will take advantage of this to analyze the effect of crossover networks on the responses of speaker drivers.

Starting MATLAB

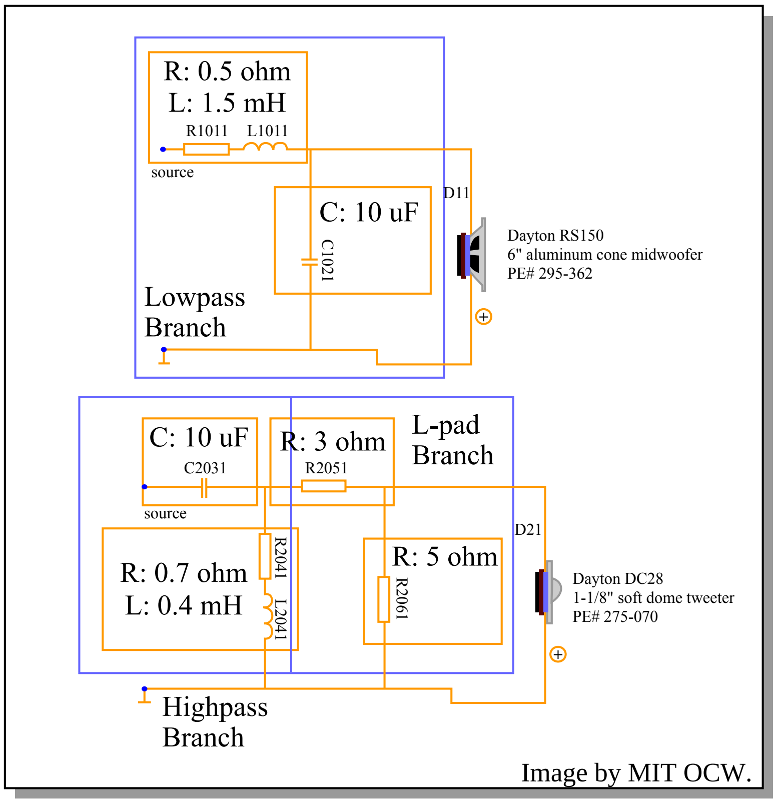
1. Start the MATLAB program: `Start -> Math/Plotting -> MATLAB`
2. Load the graphical interface: type `desktop` and hit enter.
3. Switch the working directory: on the list of folders in the upper left, double-click on `hsspmatlab`.

I had to write the functions to simulate crossover circuits; they're not included in MATLAB. To use them, you will need to change the working directory (the place where MATLAB looks for data) to the folder where I put the files, like it says in step 3 above.

You're now all set to simulate crossover circuits... let's give it a shot.

Tutorial crossover design

To help you get started, here are directions for simulating an actual working speaker design. Shown below are the crossover circuit schematics and a picture of the completed product. Does the speaker look familiar?



To simulate the response of the circuit, there are a few steps. Here are examples of the four main functions you can use. Don't enter in these exact commands... the tutorial is a couple of paragraphs down.

Example Steps for Crossover Simulation

1. Load data for each driver:
   `woofer = load('rs180');`
2. Create circuit branches:
   `lowpass = branch('RL', [0.4 2.5], 'C', 6.8);`
3. Simulate their effect on each driver:
   `highsection = simulate(lowpass, woofer);`
4. Combine networks together to form complete speaker:
   `result = combine(lowsection, highsection);`

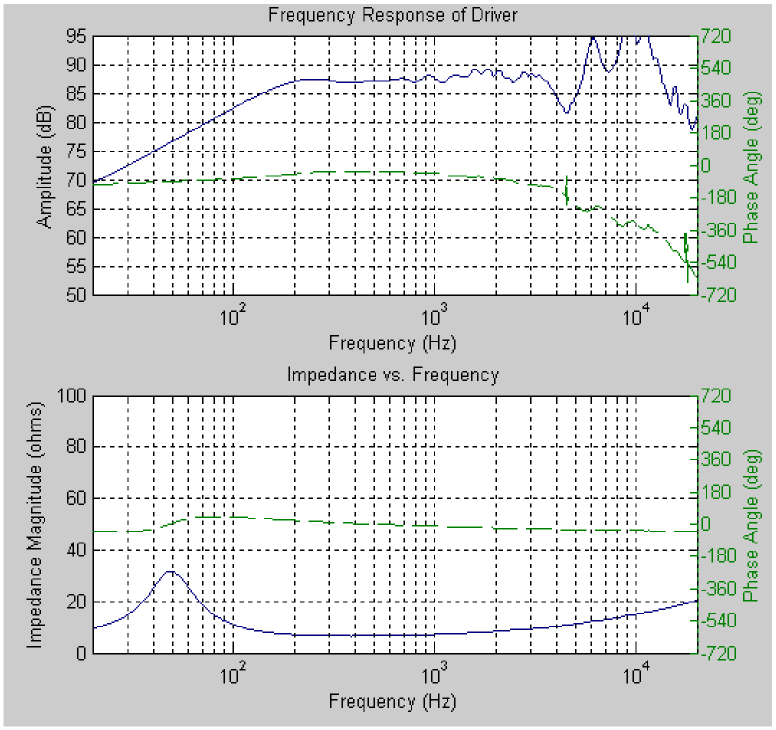
In the MATLAB command window, there's a prompt (`>>`) where you enter in lines of code for the interpreter to execute. Most of the commands you'll use for simulating crossovers involve calling a function (such as `branch`), passing that function some input data (the circuit components and their values: `'RL', [0.4 2.5], 'C', 6.8`), and receiving its output (the resulting impedance and frequency response: `lowpass`). Sometimes the code will generate a lot of numbers, which would normally go on the screen. You can enter a semicolon (`;`) at the end of a line to suppress this output if you want. I like to do it this way. Also, be careful to match up parentheses, square brackets, and quotes correctly... MATLAB can't exactly figure out what you meant to type.

Anyway, on to the circuit for the small 6" two-way speaker we've been listening to in class. This speaker uses the Dayton DC28 1" tweeter and RS150 6" woofer. The first thing you have to do is load the driver data. Enter each command and hit enter after the semicolon:

```
tweeter = load('dc28');
woofer = load('rs150');
```

Take a look at the information you just loaded. (When you're done looking at a graph, you can close it, since each plot command creates a new graph and the desktop can get crowded.)

`plotdriver(woofer);`



While I'm thinking about it, here's a summary of the various ways to display data.

Types of Output Plots

1. To plot the data for a raw driver:
   plotdriver`(woofer);`
2. To plot the response of the raw driver compared to the combination of the driver and its filter circuit:
   plotresp`(highsection);`
3. To plot the frequency response and impedance of the driver with its filter connected:
   plotimp`(highsection);`
4. To plot the electrical frequency response of the filter:
   plotgain`(highsection);`
5. To plot everything about a filter section at once:
   plotall`(highsection);`

The woofer's frequency response is pretty flat in the midrange, but it's got some nasty resonances above 4 KHz that go off the charts. You wouldn't want to listen to them, it would make music sound kind of harsh. Anyway, just keep this in mind when you're designing filter circuits; a steeper lowpass filter will do a better job of removing those peaks.

The next step is to create a description of the circuit diagram in the picture on page 2. With these functions, you can create a filter circuit of any complexity by stacking up 'branches' which describe a set of components in series with the load, and a set of components in parallel (shunting) the load. In the crossover for this speaker, the lowpass (woofer) network requires 1 branch and the highpass (tweeter) network needs 2. That's because you need to enter the actual filter part (inductor and capacitor) separately from the resistor network (L-pad) that reduces the tweeter's signal level. The numbers that you put in correspond to the values on the schematic; and when you need more than one, you have to enclose them in square brackets so MATLAB can interpret it correctly. The first branch is 0.7 Ω in series with 1.5 mH, and then a 10 μF capacitor connected across the load. Enter these in!

```
lowpass = branch('RL', [0.5 1.5], 'C', 10);
highpass = branch('C', 10, 'RL', [0.5 0.4]);
lpad = branch('R', 3, 'R', 5);
```

If you want to create a branch with no components in either the series or shunt parts, use `'none'` for the component type and `0` for the value. For example, there is a type of branch for cancelling out the rising impedance of a driver, called a 'zobel.' A typical zobel branch (placed directly in front of the driver) would look like this:

```
zobel = branch('none', 0, 'RC', [4 30]);
```

And you can also make a branch with no shunt components. This is important in a 1st-order filter where there's nothing but an inductor in series with the woofer. Here's an example. (Again, this command doesn't apply to the tutorial, though you can go back and try it if you like. Why wouldn't this be a good filter for the RS150 woofer?)

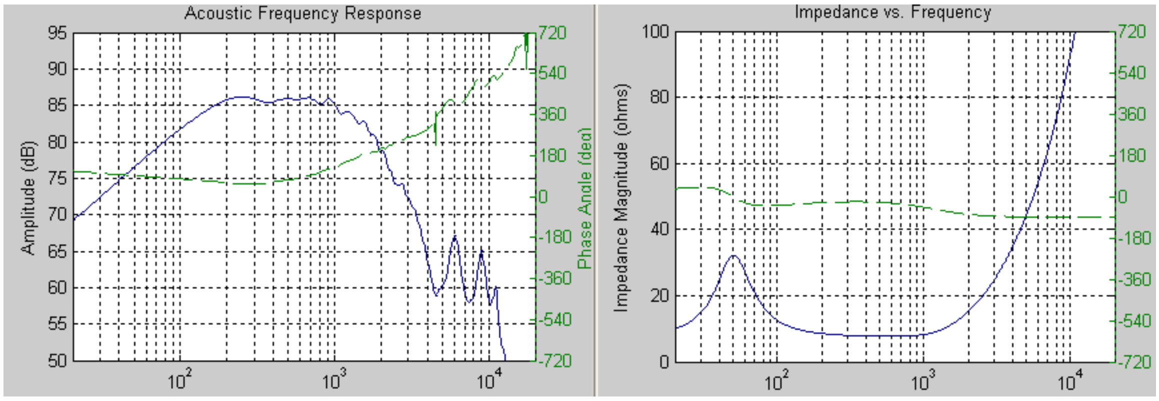
```
lp1 = branch('L', 2, 'none', 0);
```

Now, simulate the result of wiring up those filters to the woofer and tweeter. The `simulate` function produces a result containing frequency response and impedance data for each section. You can look at this data and also combine it with other results to obtain a complete prediction for the entire speaker.

```
lowsection = simulate(lowpass, woofer);
highsection = simulate([highpass lpad], tweeter);
```

Notice how in the second command, you used both the highpass and the L-pad branches connected one after the other, like the crossover schematic shows. If you connected them the other way around, like `[lpad highpass]`, the result would be different. You can try that too, if you want. Or maybe some of you can do it each way. Let's plot the result of the lowpass filter:

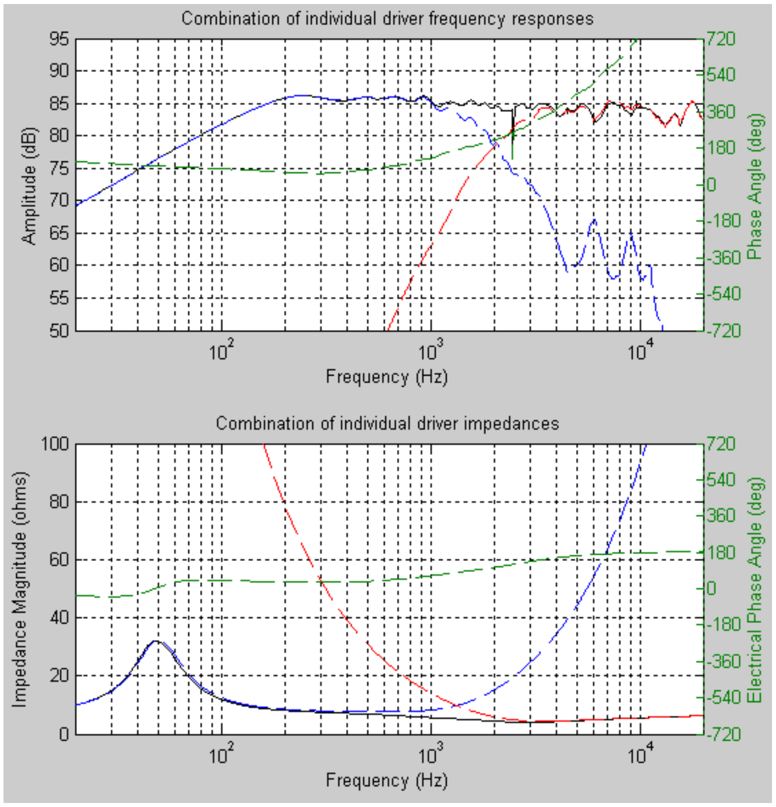
```
plotresp(lowsection);
plotimp(lowsection);
```



You can see in the frequency response that the filter has rolled off the high frequencies, supressing the bad-sounding treble peaks. And you can also see that the impedance starts to rise quickly above 2 KHz, since the inductor has high impedance at high frequencies (reducing the current going into the woofer at those frequencies).

The last step is to combine the results of the circuits connected to the woofer and the tweeter. The tweeter is connected with reverse polarity (180 degree phase shift) in order to get the phase to line up correctly between the two drivers. To simulate that, call the function `reverse` on the treble network response. This function will draw a graph even if you don't ask, because it's a pretty important graph!

```
result = combine([lowsection reverse(highsection)]);
```



That shows you how the sounds from the woofer and tweeter add together to give you full-range audio from about 80 Hz (the lower frequency limit of the woofer) to 20 KHz (the higher frequency limit of the tweeter, and also the limit of your hearing). The blue lines are the frequency response and impedance from the low frequency section; the red lines are from the high frequency section; and the black lines are the summation of the two. Notice that at the crossover frequency of 2 KHz, the woofer and tweeter are playing equally strong (79 dB) and the sum of the two is about double the amplitude (6 dB higher, or 85 dB). That's because the two drivers are in phase. If you run the simulation without reversing the phase on the tweeter, like this:

```
result = combine([lowsection highsection]);
```

then you will get a big dip in the response at the crossover frequency, since the woofer and tweeter cancel each other out. It is sometimes hard to arrange the circuit components so that the phase is well-matched. That's one of the things you get to play around with.

If you change any of the circuit branches, call `simulate` and `combine` again to re-compute the results - it doesn't happen automatically.

On to your own experiments!

Now that you have an idea about how this system works, it's time to go on and simulate any circuits you can imagine. First, pick a driver from the list below and draw out a simple filter to connect to it. Make up any reasonable values for the components and enter the circuits in using the `load, branch, simulate,` and `combine` functions. All of the information from these drivers came from the Parts Express web site, `http://www.parts-express.com`. You can find any drivers you want (navigate on the left to "Speakers"), view specifications, and download the FRD and ZMA data. There are more data files in the folder than there are drivers listed here - they'll work just as well.

Filename	**Model**	**Driver Description**	**Cost each**
tm025f1	Audax TM025F1	1" fabric dome tweeter	$15
pt2b	Dayton PT2	5" long ribbon tweeter	$32
dc28	Dayton DC28	1" fabric dome tweeter	$15
xt25	Vifa XT25TG	1" dual concentric tweeter	$54
dc50f	Dayton DC50	2" fabric dome midrange	$28
ap100z0	Audax AP100Z0	4" Kevlar/paper cone midrange	$29
rs150	Dayton RS-150	6" aluminum cone woofer	$29
rs225	Dayton RS-225	8" aluminum cone woofer	$43
rs270	Dayton RS-270	10" aluminum cone woofer	$63

Then you can get as ambitious as you want. My functions are prepared to handle as many different circuit sections as you can come up with (except maybe the plot commands). You can design a single driver speaker with a filter to flatten its response, a 2-way with two woofers in parallel, or a 3-way with a separate woofer, midrange, and tweeter.

Suggestions for crossover designs

When you try a crossover circuit, first draw it on a piece of paper. I would recommend making a nice simple diagram like the one for the example on the next page. It's much more helpful correcting it at that stage instead of running the crossover simulation only to find that things have gone wacko.

Starting Points for Crossover Design
The idea of creating circuits from scratch might seem daunting. Maybe this will help.

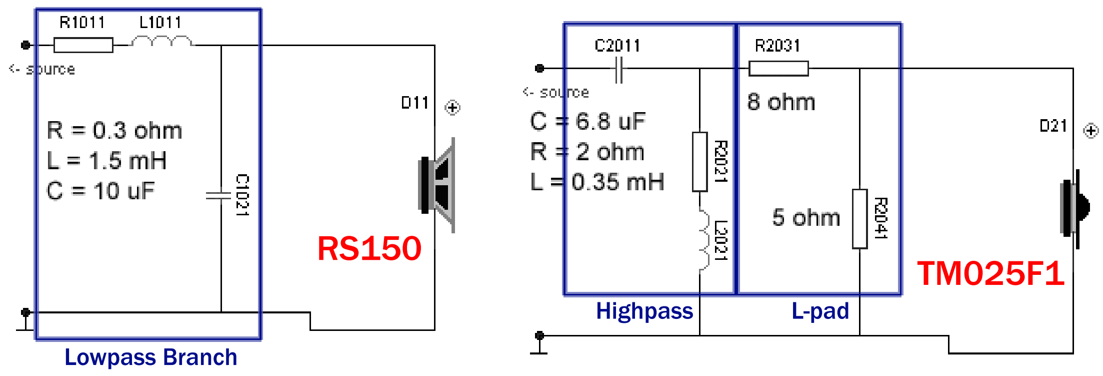
1. Don't be afraid to try out any random capacitor value that pops into your head. You are not going to hurt anything by trying to put a 1,000 μF capacitor in parallel with a virtual tweeter. In fact, maybe you'll learn something useful.
2. Try taking a look at this web page: `http://www.apicsllc.com/apics/Misc/filter2.html`
3. Enter in the "nominal" or rated impedance of each driver (usually 4 or 8 Ω) and the desired cutoff frequency.
4. It will give you values for the capacitors and inductors in mH and μF, which you can enter as circuit branches.

A 1st- or 2nd-order filter requires 1 branch per driver (plus an L-pad to reduce the tweeter level if necessary). A 3rd- or 4th-order filter needs 2 branches. As a general rule of thumb, lower cutoff frequencies require bigger component values. A 2 KHz crossover in a 2-way might use capacitors around 5-15 μF and inductors around 1-2 mH, whereas a 500 Hz crossover in a 3-way might use capacitors around 20-60 μF and inductors around 4-10 mH. If you're making a 3-way speaker, try to create two different crossover points: one between 100-500 Hz between the woofer and midrange, and one between 2-5 KHz between the midrange and tweeter. This means the midrange will have both lowpass and highpass filters attached to it (that's called a bandpass).

Here are a few ideas, pick any one and give it a shot! Think about what each of these speakers would actually look like, how much it would cost, and what **you** would want it to sound like. Draw your imaginative vision of what the speaker would look like on a piece of paper, or search the internet for similar designs. Try to come up with at least one crossover design completely from scratch. If you're able to end up with a good looking frequency response, or you've got an interesting circuit... print out the results! I would love to see them.

And, keep our class project in the back of your head. What kind of speaker do you want to build? Do you want to focus on this crossover design stuff or on something else, such as making a good subwoofer?

1. Dayton RS-150 midwoofer and Audax TM025F1 tweeter. Try playing around with it a little. What would you do to increase the crossover frequency to 3KHz?



Example Design 1
2nd order lowpass on 6" RS150 woofer
2nd order highpass and L-pad on
1" TM025F1 tweeter
Crossover frequency: 2 KHz
Tweeter polarity reversed for best response

```
woofer = load('rs150');
tweeter = load('tm025f1');
lowpass = branch('RL',[0.3 1.5],'C',10);
highpass = branch('C',6.8,'RL',[2 0.35]);
lpad = branch('R',8,'R',5);
lowsection = simulate(lowpass, woofer);
highsection = simulate([highpass lpad], tweeter);
combine([lowsection highsection]);
combine([lowsection reverse(highsection)]);
```

2. Audax AP100Z0 and Dayton DC28. This would be a really small speaker, for example a satellite in a home theater or multimedia system. I would try a simple first order crossover, with just one inductor for the woofer and one capacitor for the tweeter, at a relatively high frequency like 4-6 KHz.
3. Dayton RS225, DC50F and PT2 ribbon. The thing about ribbon tweeters is that they're fragile - you want to prevent low frequencies from reaching them, especially if the speaker is going to play loudly. So I've suggested adding a 2" midrange driver to cover the range between around 500-4,000 Hz. This is easier to work out if you try out each section with its own circuit individually before combining them.
4. Dual RS270's, RS150 and XT25 tweeter. This would be a big, rocking tower speaker. To simulate dual woofers, enter the same section name side by side when combining responses.

Have fun playing around, and don't be afraid to ask my helpful friends your questions!

How to contact me

1. Michael Price