Jason Cuadra's Elliptic Filters

Republished by permission of Jason Cuadra - contact him at "deckard at sbcglobal dot net".
(Note: His email address has been deliberately obfuscated at his request to avoid spammers.)

Editor's note: I'm grateful to Jason for agreeing to share his project and data with the DIY community. Jason has requested feedback from anyone who builds crossovers based on this design.

1st part updated 21-Feb-00

2nd part updated 9-Mar-00 (smoother summation)

3rd part updated 8-Apr-00 (active version)

This is a description of the passive crossover I "invented". It is an elliptic or Cauer filter, for those of you familiar with filter theory.

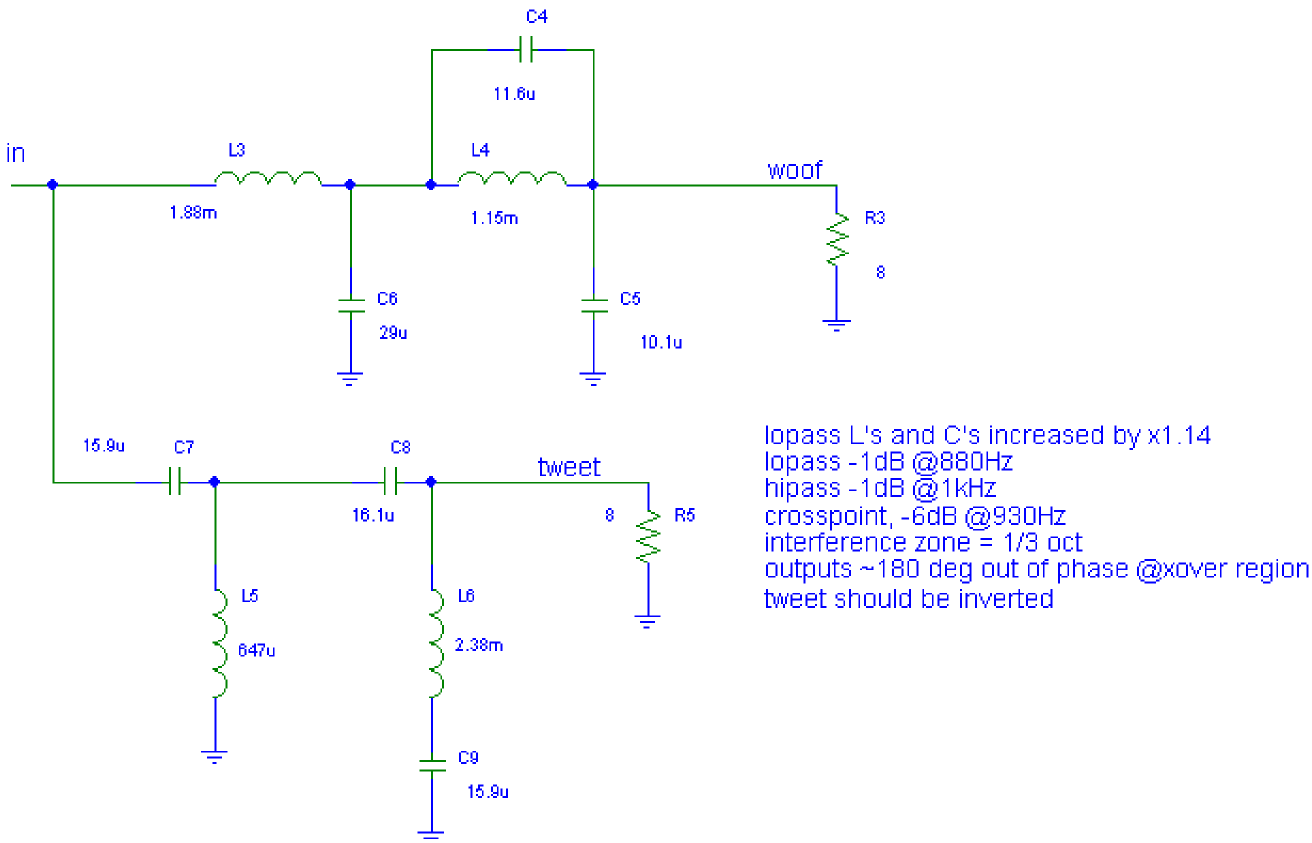
The reason I put "invented" in quotes is because this has probably been done before. See the patent by Modafferi in the IBM patent server. This is used in the Joseph Audio "infinite slope" crossovers. However, the patent uses transformers, and my xover doesn't. Funny that the patent obviously uses elliptic filters but doesn't mention them.

I took a standard 4th-order all-pole (like Linkwitz-Riley and Butterworth) filter, and added zeroes, and found the part values using CALSOD (a crossover optimizer) to get a standard elliptic filter transfer function, from a filters book. That is, I took a 4th order lopass filter, and added a capacitor across the 2nd inductor. I took a 4th order hipass filter, and added a capacitor in series with the 2nd inductor. This added notches to the response to make the slope much steeper, which is what an elliptic filter is. The slope ended up around 60 dB/octave, or like a regular 10th order but with only 5 parts. Then I checked the summing between them (the resulting signal when they play together). They weren't summing properly so I had CALSOD optimize them for proper summing. Easier said than done, but I did it.

The reason for my interest in very steep slopes is for car audio. Typical setup has the tweeters (on the dash) very far from the midranges (in the doors). Steep slopes will reduce the interference between them, and improve the imaging. Also as important, a steep slope on the tweeter means you can use a lower xover frequency, which also improves imaging. And, typical 6" car drivers with decent bass don't play the upper mids too well, making the tweets play them will sound better provided it's above their distorting frequency.

I also did an active version, with even steeper slopes, which I'll add here later.

Here is the schematic:



TO USE:

Important note: I apologize for the error but to get the predicted responses shown below, the lopass L's and C's have to be multiplied by a factor of 1.14x. You have to do this as well as the scaling below for a different xover f and driver impedance. If you don't do this the

Note, the above values are normalized for 8 ohm loads, with a crossover frequency of ~940 Hz. To change it to say 3 kHz, use the ratio of the 2 frequencies.

3000/930 = 3.23

Now make all inductors and capacitors *smaller* by a factor of 3.23.

To make it work for a non 8 ohm load, say 6 ohms, again get a scaling factor:

8/6 = 1.33

Now make all inductors *smaller* by a factor of 1.33, and capacitors *larger* by a factor of 1.33. (you are making their impedance smaller to keep pace with the load resistance)

Of course you have to do this separately for the woof and tweet.

Note also that the tweeter has to be connected out-of-phase to get proper summing (like a 2nd order butterworth).

Another thing about the above crossover is that its group delay is bad around the xover frequency. I will post curves sometime in the future, and a comparison with the LR-4 (which has a slightly lower parts count). I still believe that the merits of this crossover outweigh this downside, at the very least, in a car audio environment.

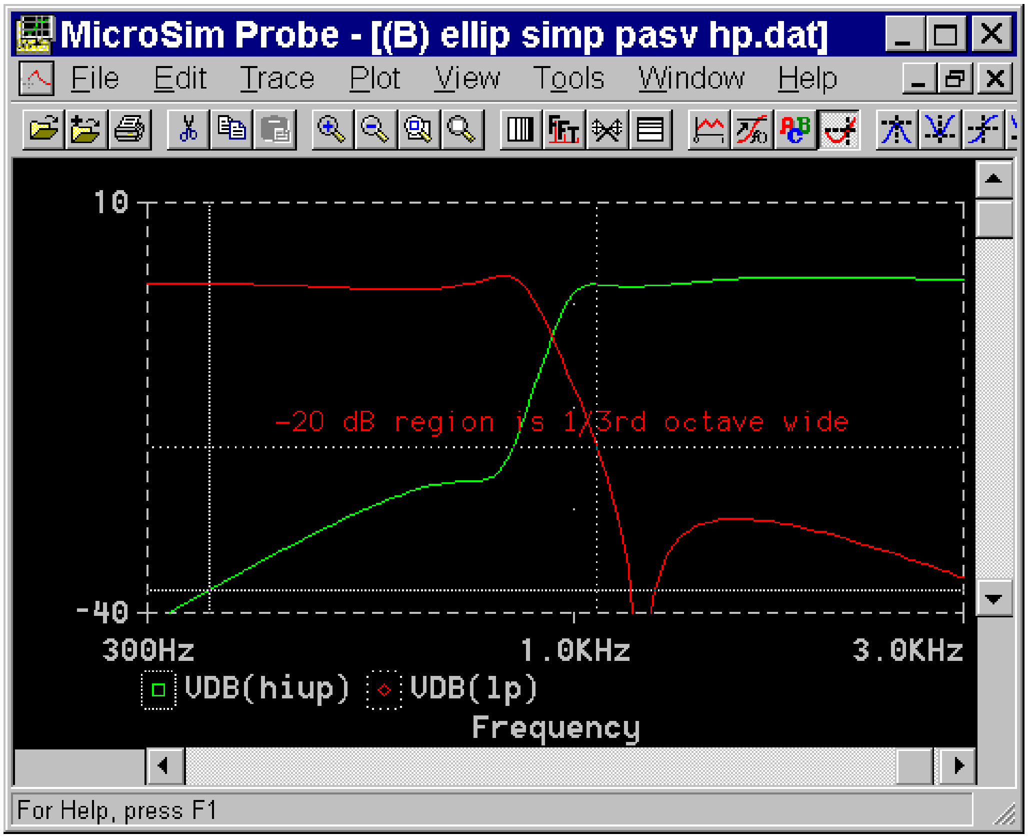
If you need to pad down the tweeter's sensitivity, you have to place a resistive divider on the tweeter. You have to know the resulting impedance that the combination of driver and resistive divider presents, to use with the xover. The circuit will have a totally wrong transfer function if you place an attenuating resistor elsewhere.

Zobels are recommended for this (and any passive xover for that matter) if the impedance of the driver is not flat near the xover frequency. The elliptic xover is more sensitive to this than others.

SIMULATION RESULTS:

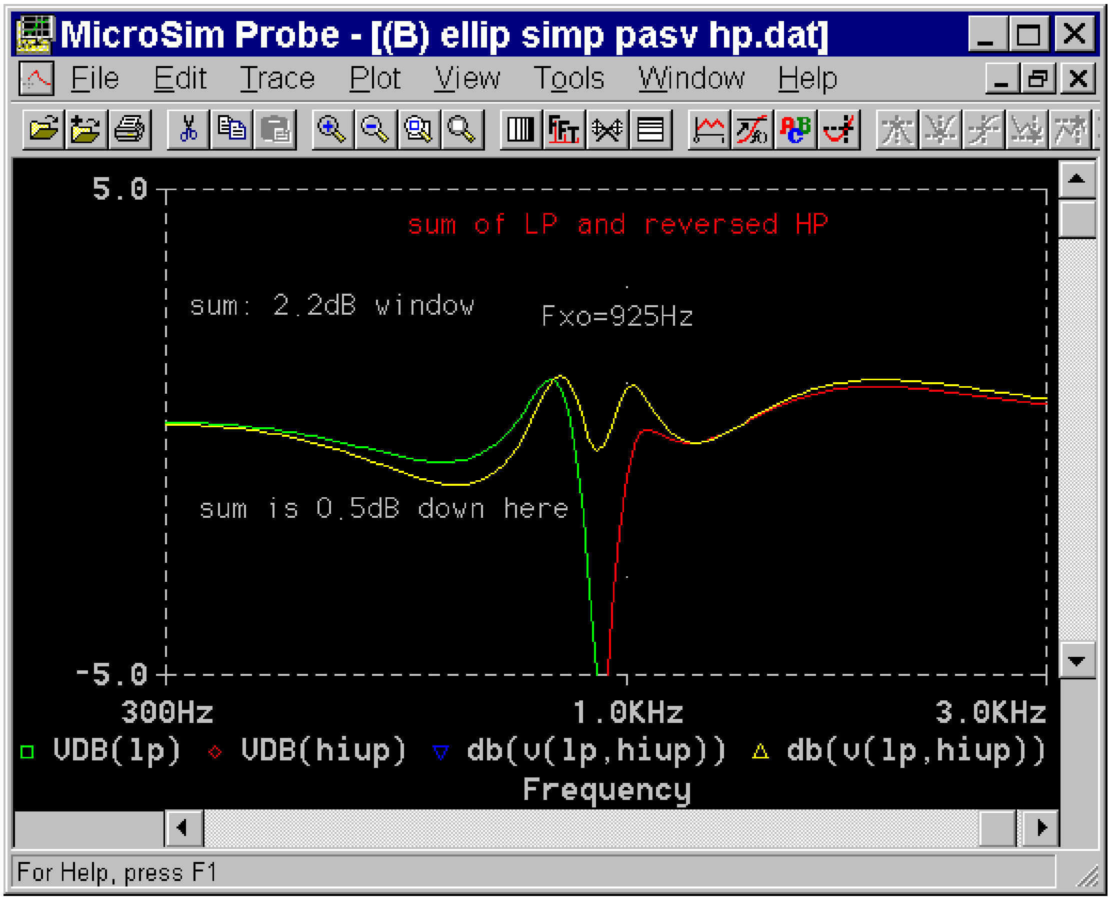
Here are the simulation results, using Pspice.

Here is the response with idealized components



The individual response are +/- .75 dB within the passband.

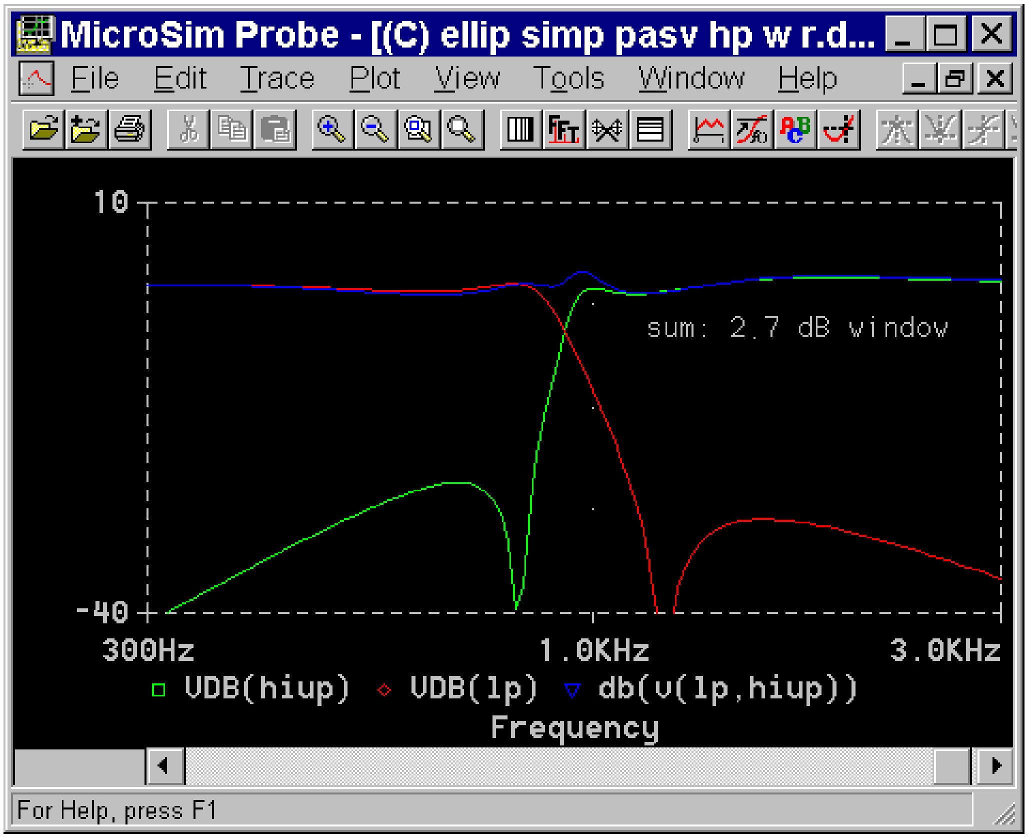
And here is the summation:



Notice that at the crosspoint they are -6dB down and sum near zero, implying they are closely in phase, like the Linkwitz-Riley crossovers. This is advantageous for home speaker designs. The summation is in a window 2.2 dB wide. They're mostly in phase, with the sum being below one driver by only 0.5 dB. See Phil's site with an explanation of this: Phil's audio site.

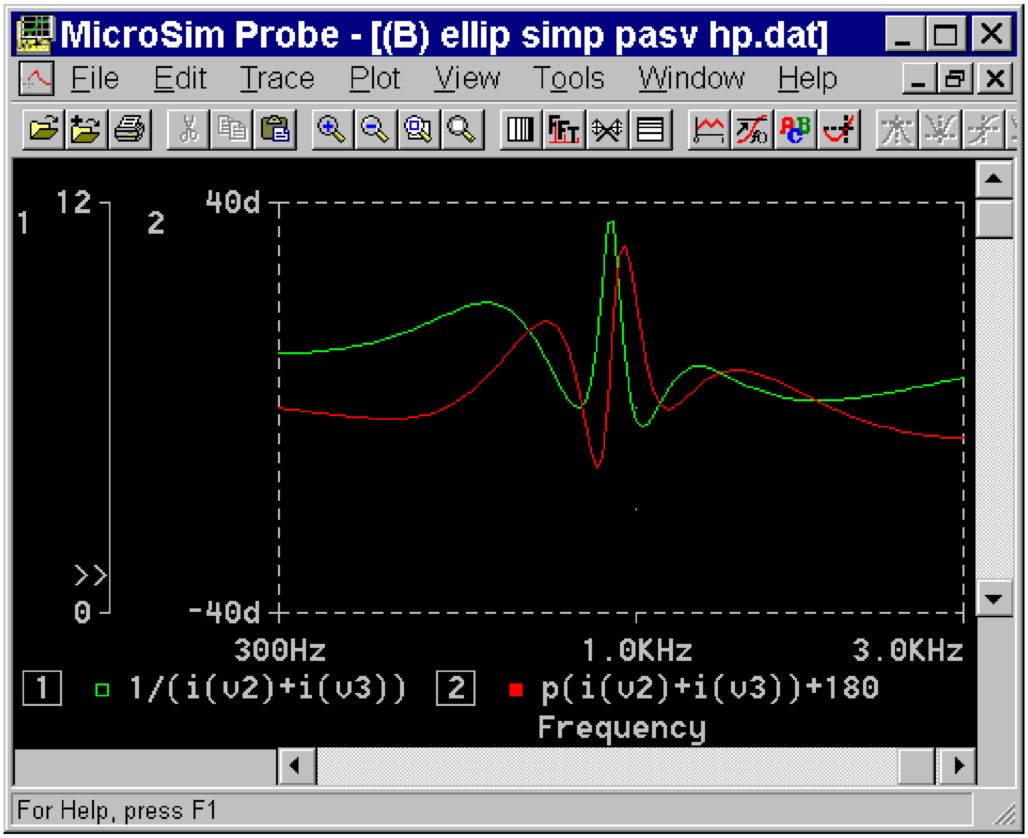
Slope is around 60dB/decade near the xover frequency. The "interference region" (region where the driver outputs interfere) where the other driver is less than -20dB down, is only 1/3rd octave wide. In contrast, for a 4th order crossover, it's 1.67 octaves wide. For a 6th, 1.1 octaves wide. Also, at 60 dB/decade, if your tweeter starts distorting at 2 kHz (or Fs is at 2 kHz) , that means you can xover at 2.8 kHz, to get 2kHz signals -20dB down. For a 4th order, you have to xover at 3.6 kHz

Here is the simulation result with non-ideal components - 0.1 ohm resistors in series with each one:



The effect was minimal. The ripple in the summation enlarged to 2.7dB, and the slope on the tweeter increased. Interference region is about the same

Here is the impedance presented to the amp with 8 ohm drivers.



Green is impedance, red is phase. Impedance dips to 5.5 ohms, and phase is + 30 degrees max. Not too bad, but with 4 ohm drivers this drops to 2.7 ohms - beware. And, the impedance if the xover is biamped is not as benign.

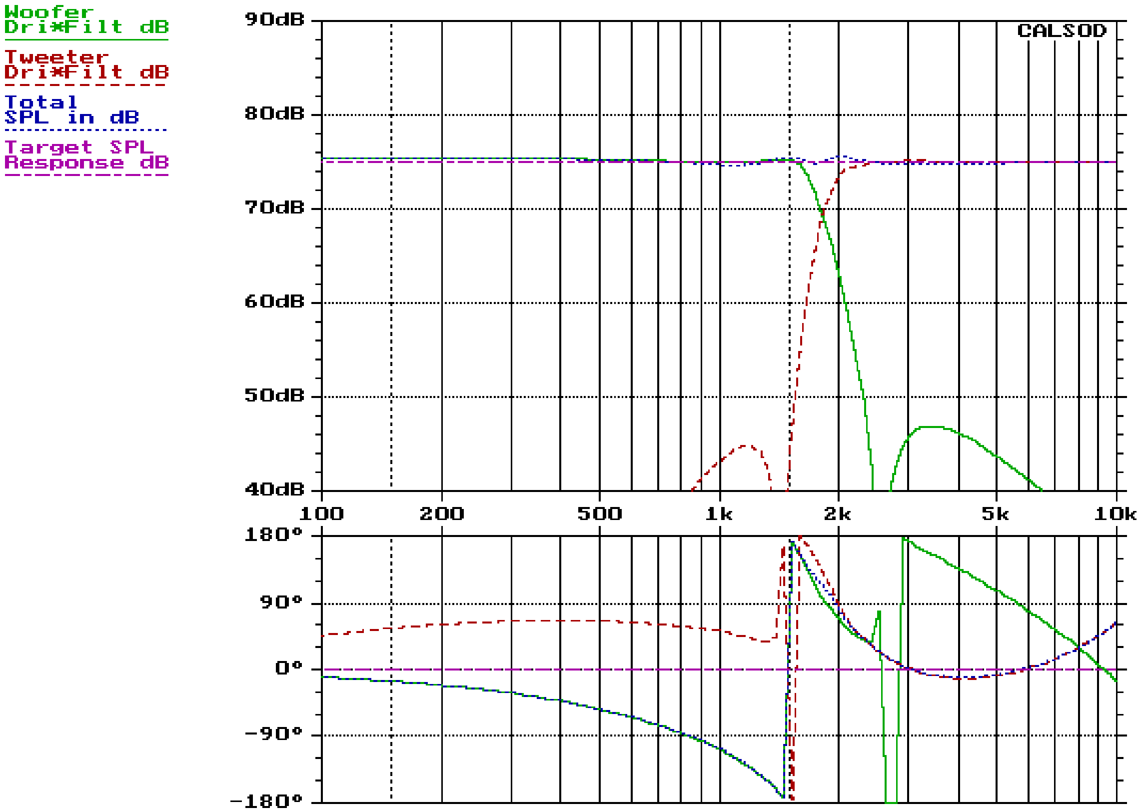
Now if you use it, you should keep a few things in mind: zobel your drivers properly and take note of the impedance presented to the amp.

When I installed this xover, at 2.4 kHz in my car system, in place of a nearly non-existent xover, the difference was very big. A huge dip in my midrange disappeared, images moved up to the dash level. See short description of my car setup.

06Mar00

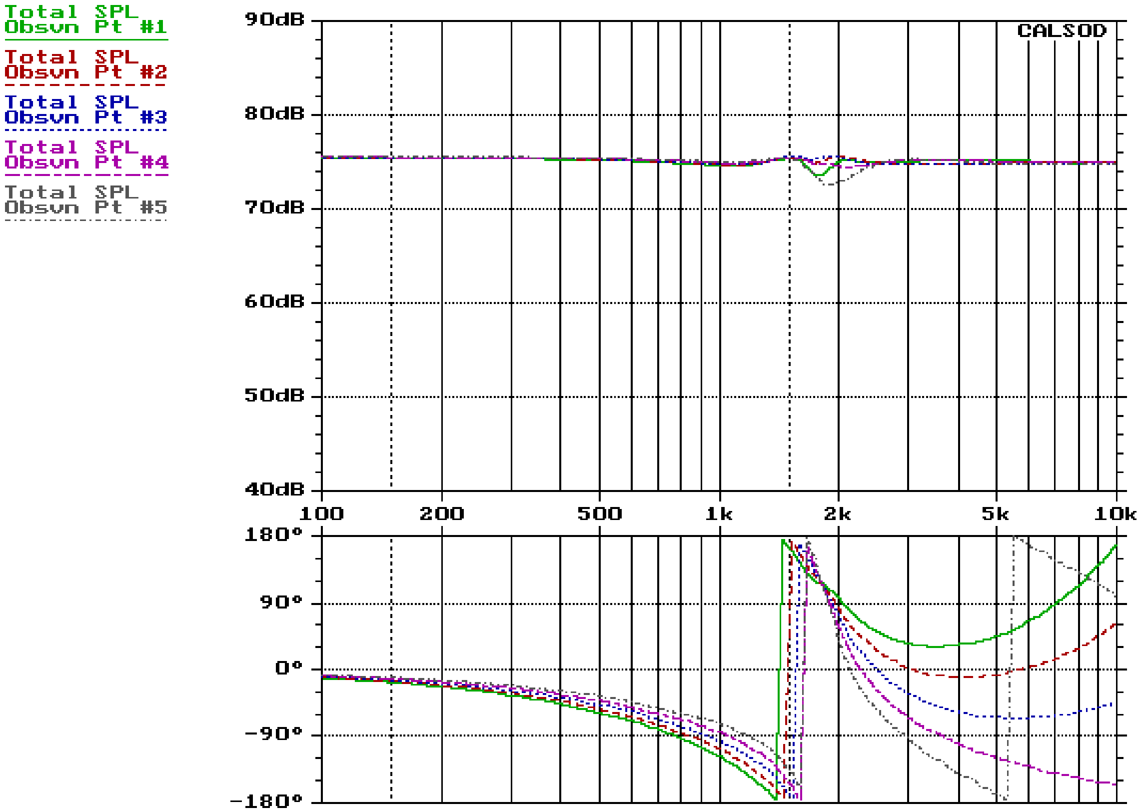
I tried optimizing the above xover further in CALSOD (a terrific xover optimization and simulation package), this time to get smoother summation. The result is that the -20dB region is 1/2 octave instead of 1/3rd octave, and the elliptic "humps" are -30dB instead of -24dB. Here are the results: (Note I let all inductors have 0.2ohms DCR - this translates to 0.4 dB loss for 8ohm drivers for the lopass)

Summation:



Note the much smoother summation, and that the stopband "humps" are -30dB below the passband.

Off-axis



The off-axis plots are done as follows:

- drivers are vertically offset by a center-to-center distance of 12cm (~2/3rd wavelength @ 1800 Hz) with tweeter above.

- midrange is sitting 2 cm back from the plane of the baffle

- listening position is 2m away.

- observation points are:

--20^{o} above

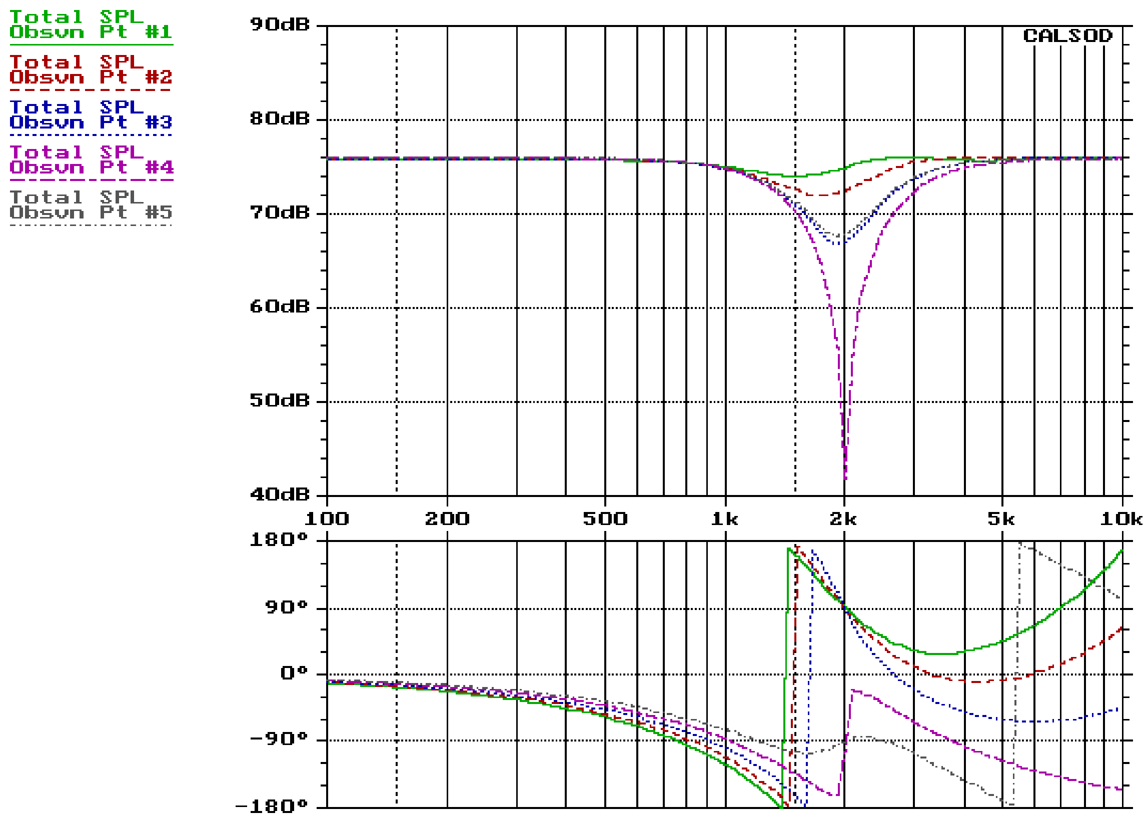
--10^{o} above

--0^{o} above

--10^{o} below

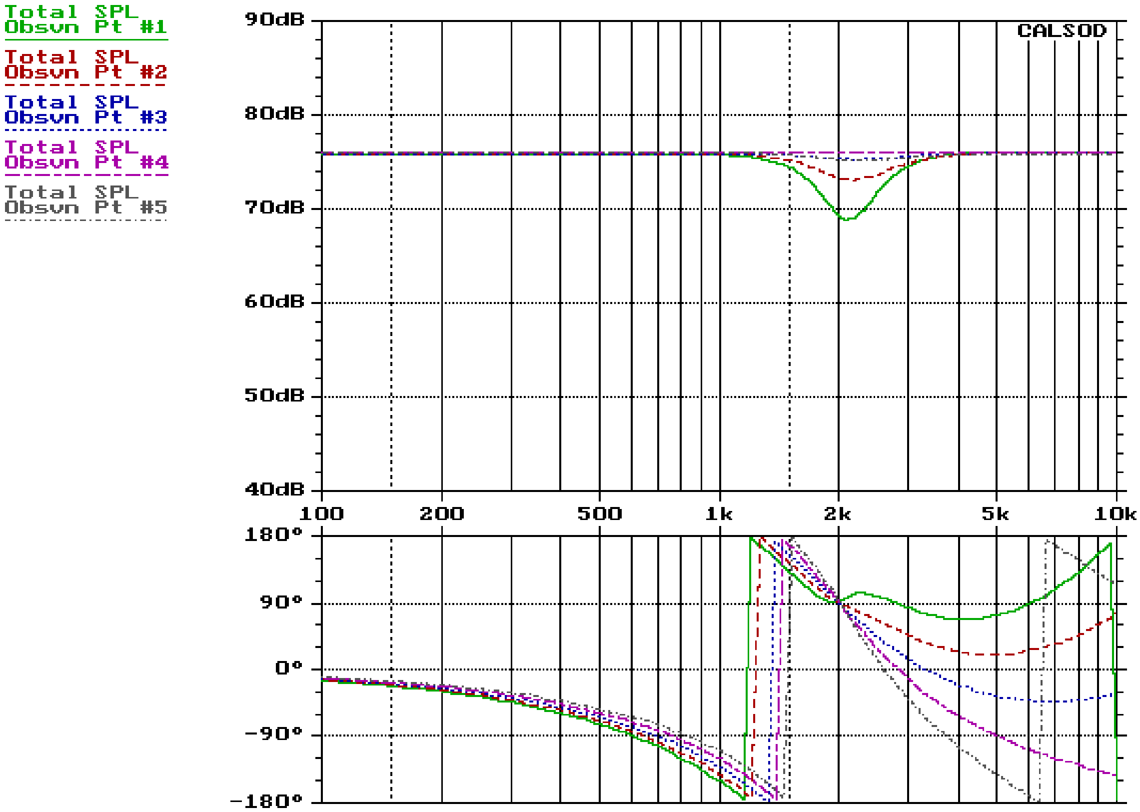
--20^{o} below

Now here is a comparison with a 4th order Linkwitz-Riley:



Note how superior the off-axis performance of the elliptic xover is compared to a 4th order L-R, for the cost of an extra capacitor!

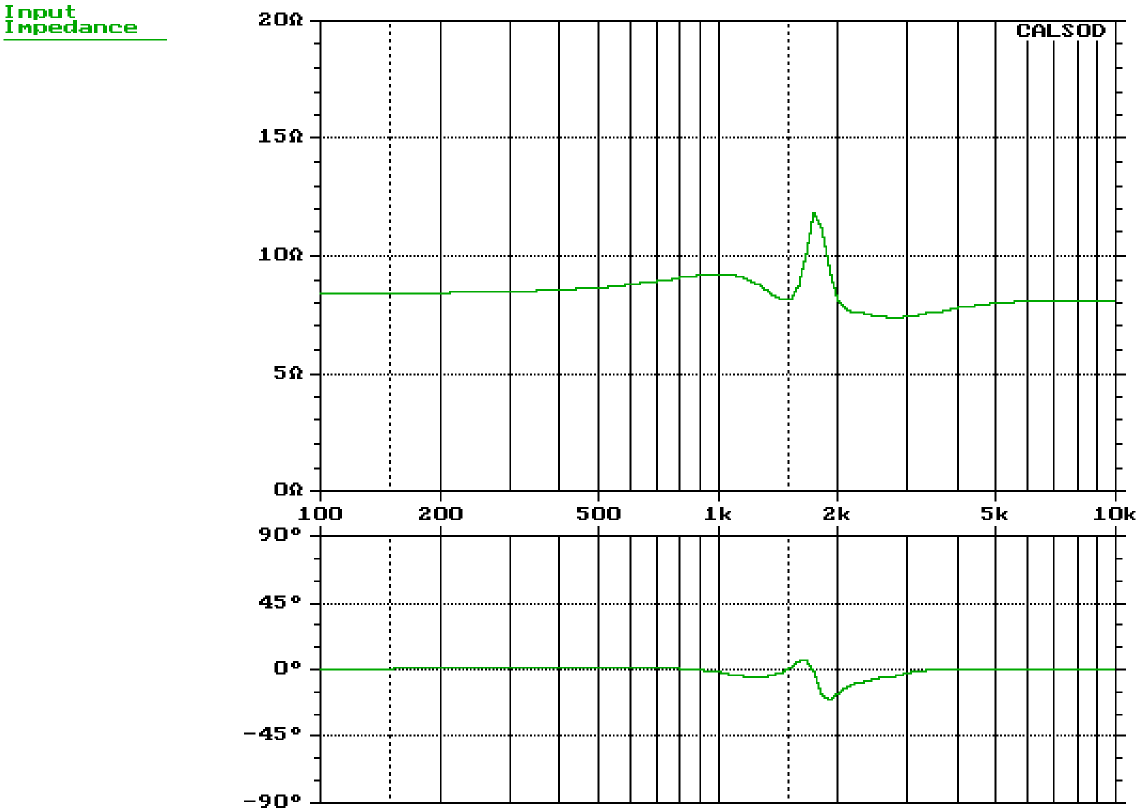
Now here is a comparison with a **6th** order Linkwitz-Riley:

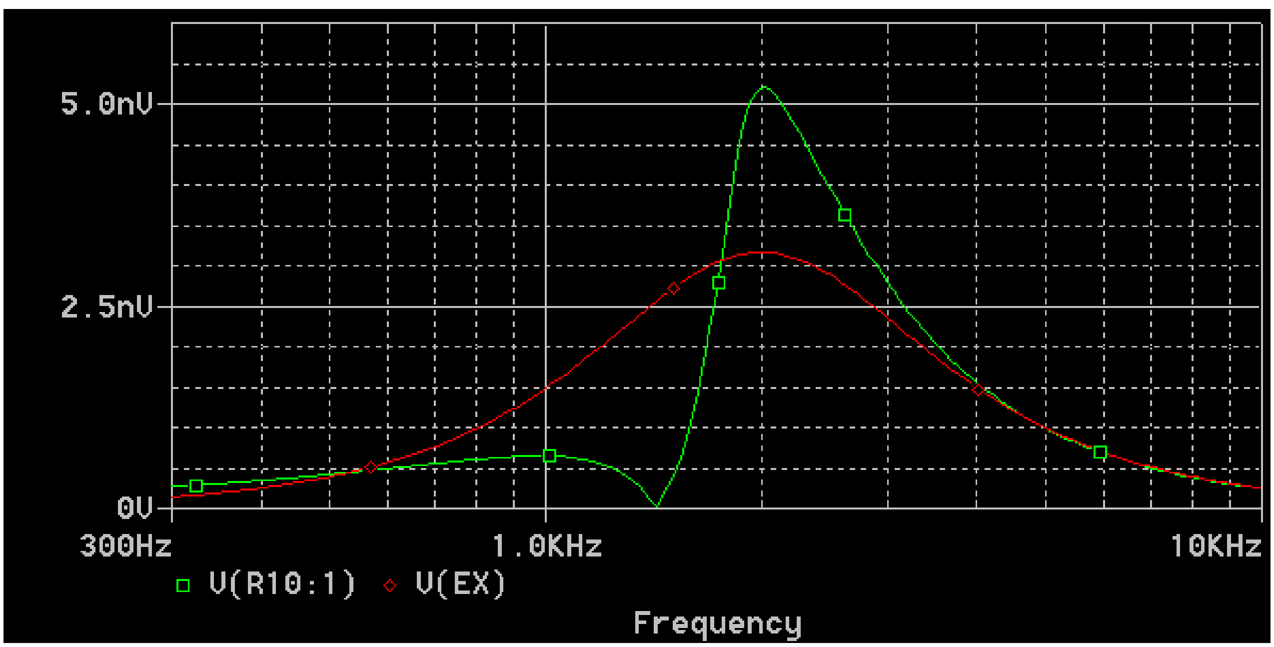


The elliptic is still superior, with one less inductor.

Note that the comparison was for my elliptic topology at 1800 Hz vs. an L-R at 2000 Hz. We know that for a given driver separation, the off-axis performance worsens at higher xover frequencies. This is not a fair comparison of off-axis performance.. for the elliptic! If your tweeter begins to distort at (or has an Fs of), say, 1500 Hz, you can xover it with this elliptic at 1800 Hz, because this elliptic will be better than -20dB by 1500 Hz - whereas an LR-6 would have to be xovered at 2.2 kHz to get -20 dB by 1500 Hz, and an LR-4 at 2.7kHz(!) to get -20 dB at 1500 Hz.

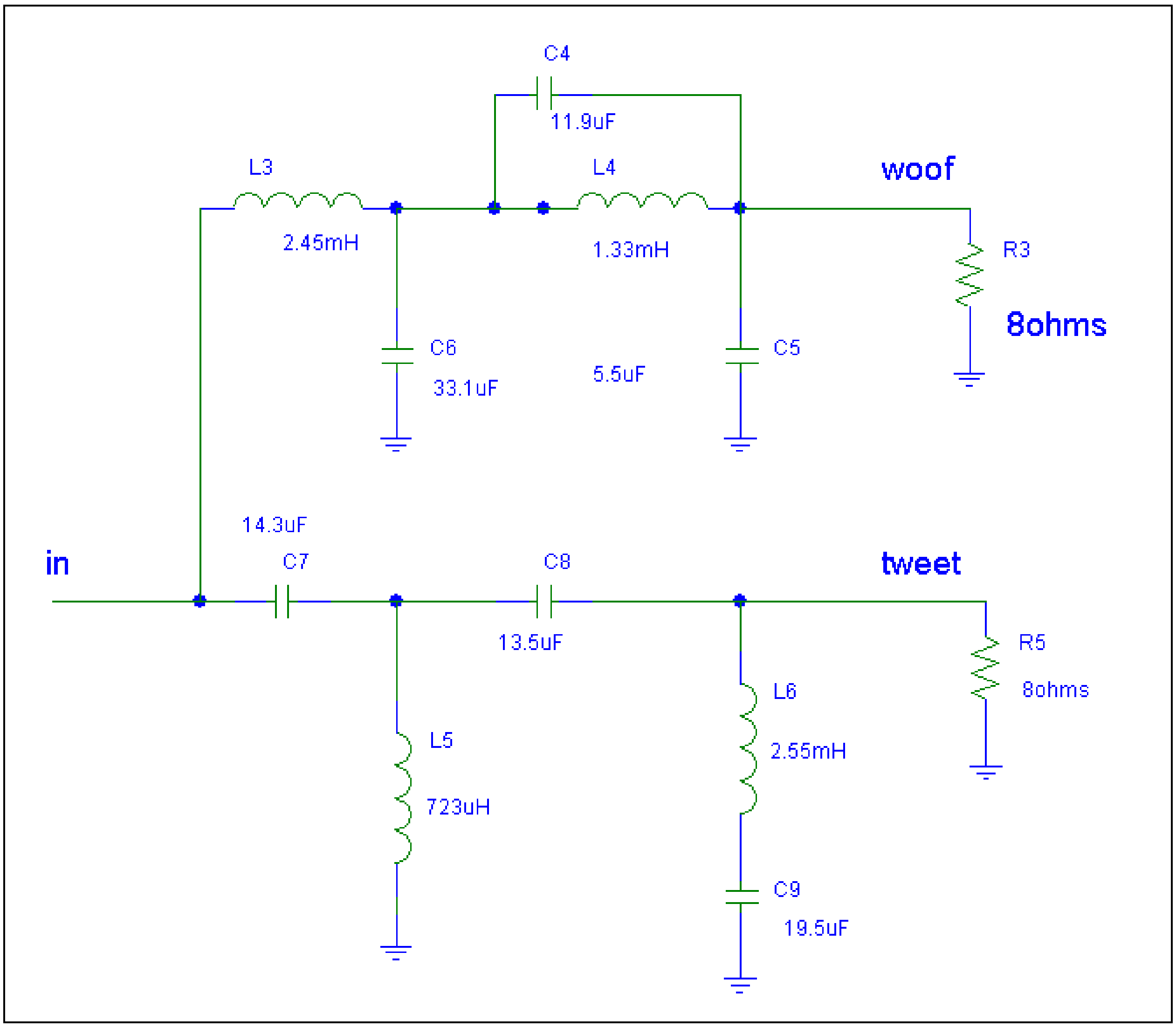
Input impedance:





Note that the excursion is much reduced in the 800 Hz to 1.8 kHz region. The slope of the elliptic below 500 Hz is around the same as a regular 2nd order xover. But by this point the excursion is so low this fact doesn't matter.

Here are the part values:



IMPORTANT: The above values are for 8 ohm loads, and a crossover frequency of 900 Hz. The resistors represent the drivers. Do not add them!

To change it to say 2.7 kHz, use the ratio of the 2 frequencies.

2.7kHz/900Hz = 3

Now make all inductors and capacitors *smaller* by a factor of 3 (smaller if desired xover frequency is higher)

To make it work for a non 8 ohm load, say 6 ohms, again get a scaling factor:

8/6 = 1.33

Now make all inductors *smaller* by a factor of 1.33, and capacitors *larger* by a factor of 1.33. (you are making their impedance smaller to keep pace with the load resistance) (Do the opposite if driver impedance is greater than 8 ohms)

Of course you have to do this separately for the woof and tweet.

Note also that the tweeter has to be connected out-of-phase to get proper summing (like a 2nd order butterworth).

I'd say this 2nd one is better for a home speaker system, because of the better summation, but the 1st one is better for a car system, because of the narrower frequency overlap region (steeper slopes)

Note that I would recommend starting with the above crossover but optimization is still necessary to take the individual driver response into consideration. The above then is an "ideal crossover" which is the starting point. Proper zobels of course should be used.

08Apr00

PART 3, **ACTIVE VERSION**

It was difficult and tedious, but I did it, an active version. It took a lot of coaxing CALSOD to 1st, find the filter curve, then 2nd, optimize the summation. This time I made it for 100 Hz, which is closer to a typical active subwoofer xover frequency, where an active filter would more typically by used. It was also borne out of need, because I got tired of poor integration between my sub and mains. My active filter implementation is low-parts count, and low-component-sensitivity to boot. I wanted it low-parts count for the simple reason that I'm lazy when it comes to assembling my circuits, I'd rather think up a smarter, lower parts count circuit than slog thru building a complicated one. The low component sensitivity thing I wanted for performance reasons, and so I wouldn't have such a hard time hand-measuring and picking capacitors.

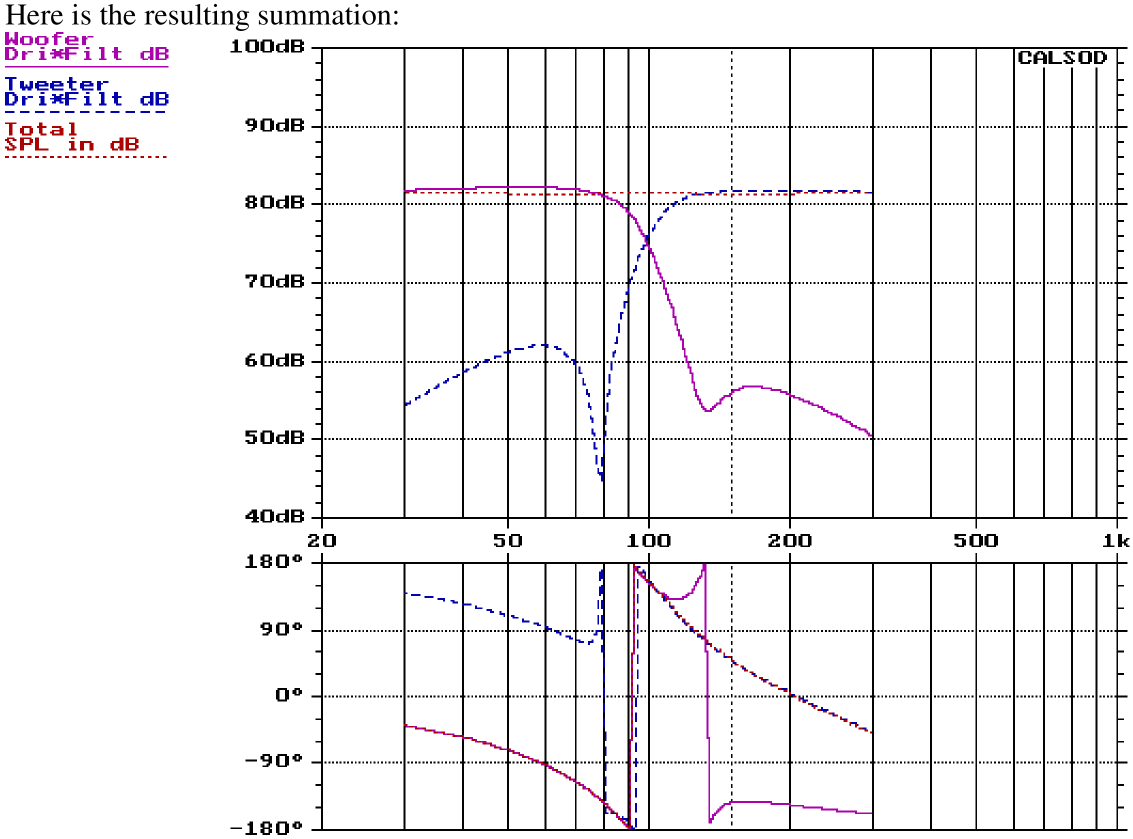
I did the low-sensitivity part out of a "gyrator" implementation. I made it low parts count by using 1-opamp-3-passive-parts gyrators, instead of using a more idealized, 2-opamp-5-passive-parts type gyrators. The latter gyrators simulate an ideal inductor, the former, an inductor with a parasitic series resistor. With careful design, one can make the parasitic series resistor insignificant.

To be precise, the lopass filter gyrator doesn't simulate inductors, but FDNRs (frequency dependent negative resistor). See article on gyrators. Thanks to Kent Dillin of the EEdesign mailing list on http://www.onelist.com. This 1 opamp FDNR I figured out by looking at the equation for impedance of the inductor gyrator and figuring out that if I swapped R"s for C's and vice versa I would get an FDNR :-).

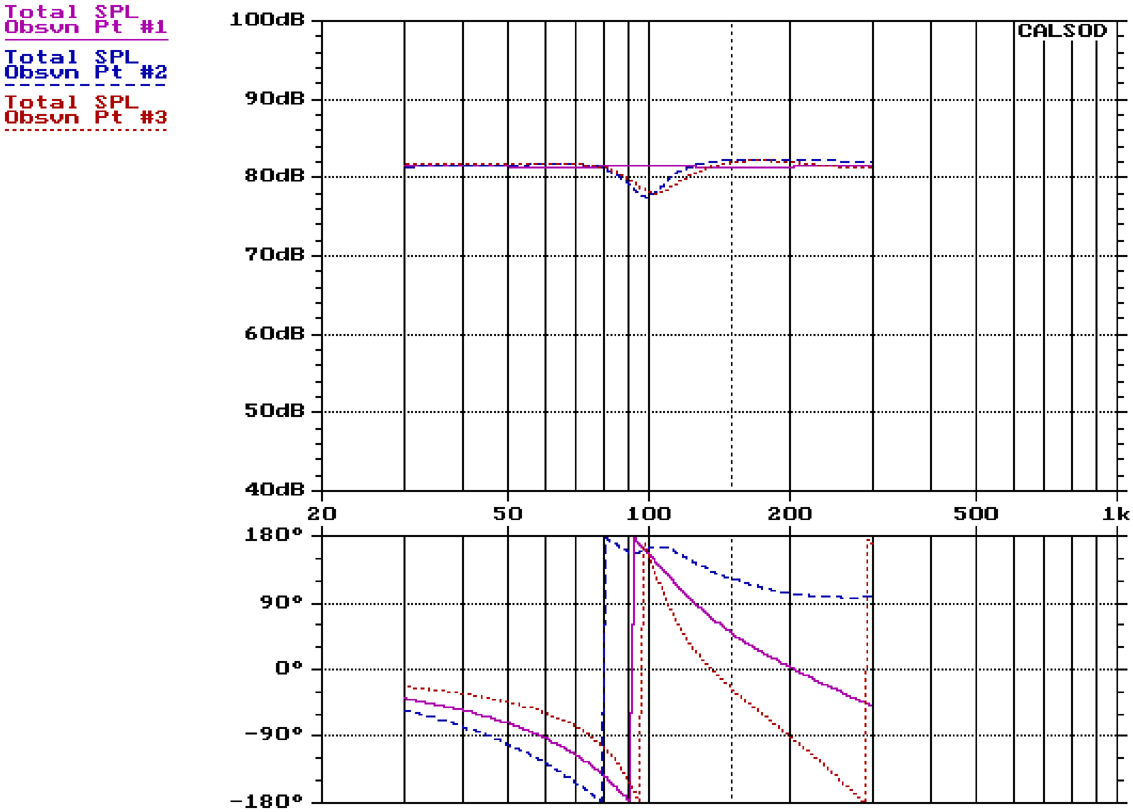
I also have this book as a reference. It however, doesn't describe the 1-opamp gyrator. Actually I **think** it's this one, because I can't find it at the moment:

Active and Passive Analog Filter Design : An Introduction (McGraw-Hill Series in Electrical and Computer Engineering. Computer Engineering)
ISBN: 0070308608, by Lawrence P. Huelsman
(Note that this book is oficially out of print, but you can still find it at AddALL.com.)

Here is the resulting summation:



And the off axis response:



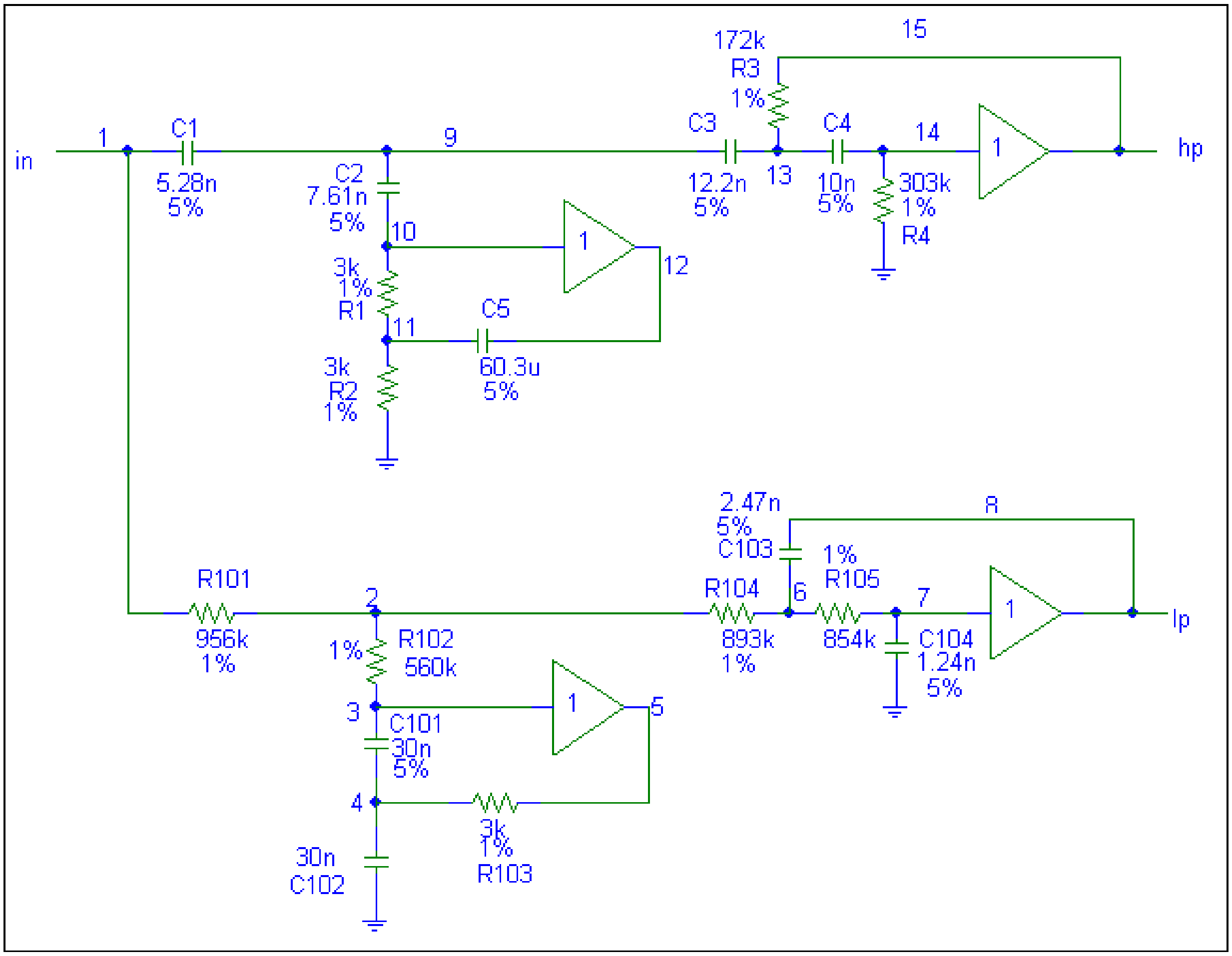
Note that it is, like all good crossovers, in-phase through the crossover region, and produce a flat summation, but IF the subwoofer is closer to the listener by 1/12th of a wavelength. But don't worry, if they're equidistant the resulting dip in the summation is circa 1 dB.

Note also that the -20 dB "interference region" is only 1/2 octave wide. Contrast this with a 4th order Linkwitz-Riley which would be around 1.6 octaves wide. This active xover acts something like an 8th to 10th order Linkwitz-Riley, with far fewer parts and smaller variations due to part variations.

This crossover of course can be used at say, 2 kHz, or some other frequency for a mid to tweet crossover. All you have to do, is make all capacitors smaller by a factor of 20 (which is the ratio of 2000 Hz to 100 Hz). One potential problem though is some of the capacitor values become hundreds of pF, and it may be more difficult to get plastic caps in that range. Don't use ceramics, they're too temperature dependent, and besides, golden-eared types don't like them. :-) Actually I'm not golden-eared but I still wouldn't use them.

Not shown is the effect of 1% tolerances on the resistors and 5% on the capacitors. I did a Monte Carlo analysis, because active filters can be more sensitive to component variations. A Monte Carlo analysis is where Spice will make several runs, with each part's value randomized to within the component tolerance. I did 20 runs, and found the worst case to be +.75, -1.5 dB. Pretty good, which shows that this filter is pretty insensitive to component variations. I at first tried a "Friend biquad" filter section to implement the filter zeros, but that was pretty sensitive to component variations, especially the hipass section, for some reason.

Here is the schematic



The triangles with a '1' in them are voltage followers - use your favorite opamp. Mine are LF347 and TLC2274.

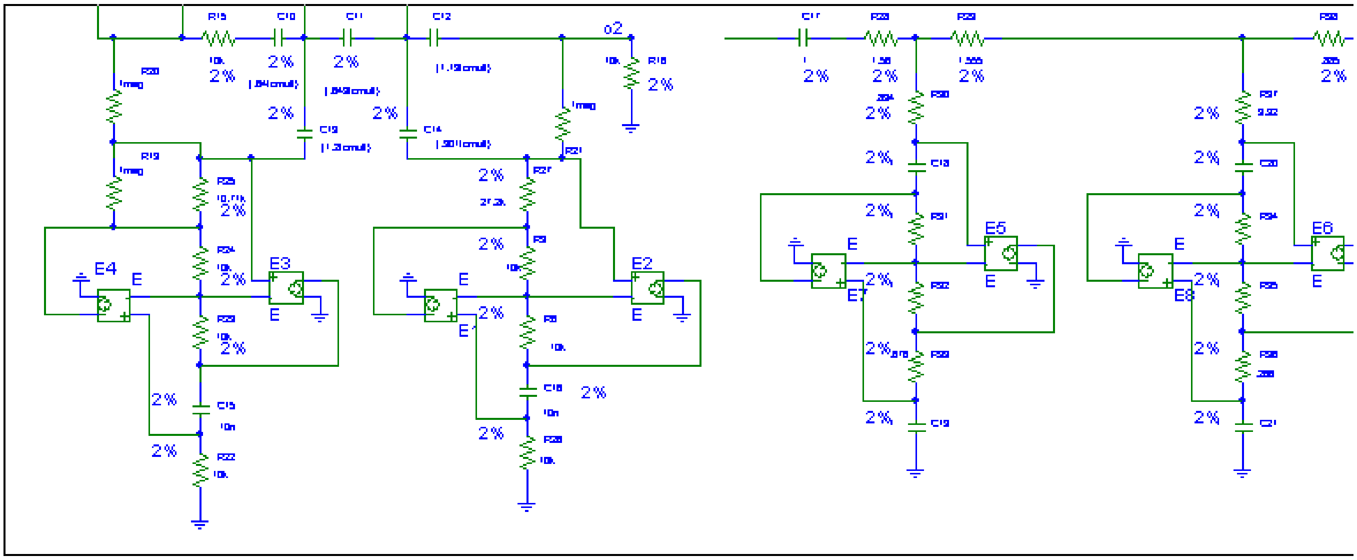
Like all active filter circuits you should drive their inputs with a buffer. For a mono sub this buffer can be a summer too, so you only need a single lopass filter stage. For car audio the input stage should be differential to prevent noise problems. Something many car audio amp manufacturers scrimp on, with resulting noise problems.

The numbers 1 through 15 are just node numbers, for the CALSOD file generation.

The first opamp in each filter forms the gyrator, the 2nd forms a Sallen-Key 2nd order filter. To be precise, the gyrator section impelements a pail of poles and zeros, and the S-K section impements a pair of poles - a 4 pole 2 zero elliptic.

As you can see, parts count is only 2 parts more than a 4th order Sallen-Key crossover, but with much steeper steeper transition.

Just for fun, here is a 2 opamp gyrator implementation of a 5th order elliptic filter:



Whew!!! Good thing I was able to reduce the parts count by a factor of 3!

Following are the various CALSOD files I used for some of the above optimizations:

! ------------------------------

! DATA FILE FOR A TWO-WAY SYSTEM

! Elliptical xover

! ------------------------------

!

! Optimizer frequency range : 1 kHz to 20 kHz

! Optimizer subintervals : 20

!

CIRCUIT

!

! Filter network for the woofer

!

ind 2.446E-03 1 2 2.000E-01 var

```
cap 3.311E-05 0 2 var
ind 1.331E-03 2 3 2.000E-01 var
cap 5.492E-06 0 3 fix
cap 1.193E-05 2 3 fix !parallel, for elliptic
SPK 1 0 3 0.0 -0.2 0 POSITIVE
!
! Filter network for the tweeter
!
CAP 1.428E-05 1 4 VAR
IND 7.235E-04 0 4 2.000E-01 VAR
CAP 1.353E-05 4 5 var
IND 2.553E-03 5 6 2.000E-01 var
CAP 1.951E-05 0 6 var
SPK 2 0 5 0.0 0.2 0 NEGATIVE
!
TARGET SPL
!XYZ 0.0 0.0 0.0
SEN 75 DB
RAB 2.0 15.0 0.0 .75 ACTIVE
RAB 2.0 5.0 0.0 .75 ACTIVE
RAB 2.0 -5.0 0.0 .25 ACTIVE
!
DRIVER 1
Woofer
!
SOUND PRESSURE
```

SEN 82.0 DB

!

IMPEDANCE

ICR 8

!

!

DRIVER 2

Tweeter

SOUND PRESSURE

sen 81 db

IMPEDANCE

ICR 8

—

This is the CALSOD file I used for finding the component values of the standard lopass elliptic filter:

====================

LOPASS "Ellip.fil"

====================

! --

! FILE FOR FINDING VALUES FOR ELLIPTIC LOPASS

! --

!

! Optimizer frequency range : 250 Hz to 6 kHz

! Optimizer subintervals : 20

!

CIRCUIT

IND 7.668E-04 1 2 0.000E+00 variable

CAP 1.331E-05 0 2 variable

IND 2.629E-04 2 3 0.000E+00 variable

CAP 1.520E-05 2 3 variable

CAP 2.436E-06 0 3 variable

SPK 1 0 3 0.0 0.0 0.0 POSITIVE

!

TARGET SPL

XYZ 0.0 0.0 0.0

SEN 90.0 DB

TFN 2200 3 5

1.31 0 1

.498 .875 1.6 .929 1

!

DRIVER 1

Woofer

SOUND PRESSURE

SEN 98.4 DB

IMPEDANCE

ICR 8

This is the CALSOD file I used for finding the component values of the standard hipass elliptic filter:

IOW this is how I found the component values for a

================

FILE "ELIPHP.FIL"

================

```
! ----------------------------------------
! DATA FILE FOR WOOFER WITH A FILTER ADDED
! ----------------------------------------
!
! Optimizer frequency range : 250 Hz to 6 kHz
! Optimizer subintervals : 20
!
CIRCUIT
IND 7.668E-04 1 2 0.000E+00 variable
CAP 1.331E-05 0 2 variable
IND 2.629E-04 2 3 0.000E+00 variable
CAP 1.520E-05 2 3 variable
CAP 2.436E-06 0 3 variable
SPK 1 0 3 0.0 0.0 0.0 POSITIVE
!
TARGET SPL
XYZ 0.0 0.0 0.0
SEN 90.0 DB
TFN 2200 5 5
0 0 1.0 0 1.31
1.0 .929 1.602 .875 .498
!
```

DRIVER 1

Woofer

SOUND PRESSURE

SEN 98.4 DB

IMPEDANCE

ICR 8

! ------------------------------

! active elliptic using gyrators

! ------------------------------

!

! Optimizer frequency range : 30 Hz to 300 Hz

! Optimizer subintervals : 100

!

CIRCUIT

!

! Filter network for the woofer

res 9.559E+05 1 2 var !R1 !first lopass R, on gyrator ladder

res 5.587E+05 2 3 var !R2 !notch res, of gyrator, sets notch freq

res 3.000E+03 4 5 fix !R3 !gyrator res, always fixed, sets gyr opamp load imp cap 3.000e-08 3 4 fix !C1 !gyrator cap

cap 3.000e-08 0 4 fix !C2 !gyrator cap must be same as C1

! SK SECTION

res 8.929E+05 2 6 var !R4 sk res

res 8.538E+05 6 7 var !R5 sk res

cap 2.475E-09 6 8 var !C3 sk cap

cap 1.241E-09 0 7 var !C4 sk cap

ioa 5 3 5

ioa 8 7 8

SPK 1 0 8 0 -1.8 0 POSITIVE

! HIPASS NETWORK

cap 5.284E-09 1 9 var !C1 !first hipass on gyrator

cap 7.611E-09 9 10 var !C2 !notch cap on gyrator, sets notch f

cap 6.031E-05 11 12 fix !C5 gyrator cap

```
res 3e3 10 11 fix !R1 !gyrator R always fix, sets opamp load imped!
res 3e3 0 11 fix !R2 !gyrator R always fix

! SK section

cap 1.219E-08 9 13 var !C3 sk cap
cap 1.006E-08 13 14 var !C4 sk cap

res 1.721E+05 13 15 var !R3 sk r
res 3.032E+05 0 14 var !R4 sk r

ioa 12 10 12
ioa 15 14 15

SPK 2 0 15 0 1.8 0 .0008 POSITIVE

TARGET SPL
!XYZ 0.0 0.0 0.0
SEN 81.4 DB
!RAB 16 0 0 1 ACTIVE
RAB 32 0.0 0.0 .75 ACTIVE
RAB 32 15.0 0.0 .13 inACTIVE
RAB 32 -15.0 0.0 .13 inACTIVE
!

!
```

DRIVER 1

Woofer

SOUND PRESSURE

sen 111.5 db

!mpe 300 9 6 dB

IMPEDANCE

ICR 8

DRIVER 2

Tweeter

SOUND PRESSURE

sen 111.5 db

!mpe 60 9 -6 db

IMPEDANCE

ICR 8