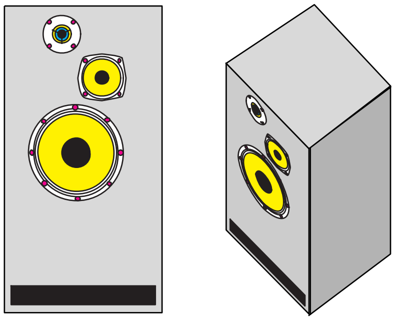
Application Note 5

Analog Audio Active Crossover

Highlights

Importing Transducer Response Data
Generic Transfer Function Modeling
Circuit Optimization
Cascade Circuit Synthesis



■ Design Objective

3-Way Active Crossover
4th Order Crossover
200Hz/2kHz Crossover Points
Optimized Response

This design will provide an example of how to integrate many of the powerful features in the software, to produce a custom analog active crossover.

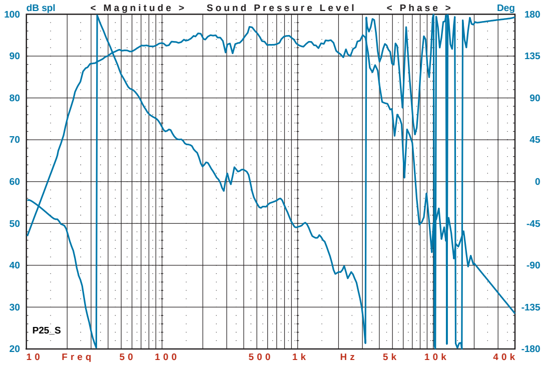
Active crossovers utilize separate amplifiers for each section, with the transducers connected directly to the amplifiers. As such the impedance of the transducers is not involved in the crossover design.

■ Prototype Data

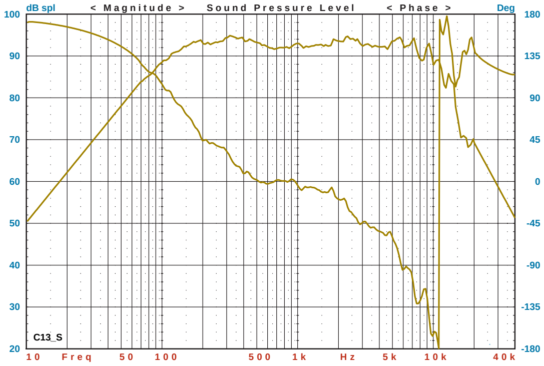
We will assume that a prototype 3-way enclosure has been constructed, similar to that shown above, and that SPL data has been obtained for each of the three sections: Woofer, Midrange, and Tweeter. This data is measured prior to the use of any crossover, and reflects the response of each section measured separately.

The three graphs on the following page show the SPL Magnitude and Phase for each of the three transducers, measured using a 10Hz to 40kHz frequency range.

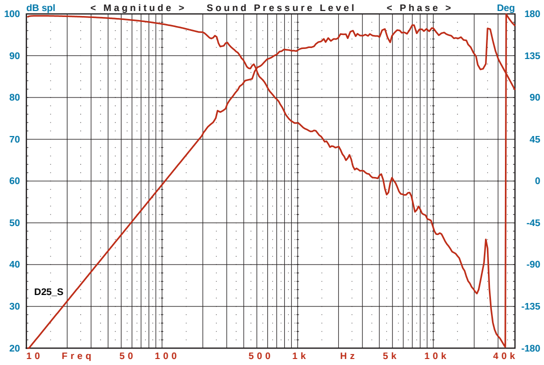
Measured phase data may or may not contain the absolute position (delay) information. In this case it does not. The SPL phase measurements for each of the three transducers are relative to the acoustic origin (voice coil) location. Consequently, we will need to handle the true time position separately.



Woofer SPL Response



Midrange SPL Response

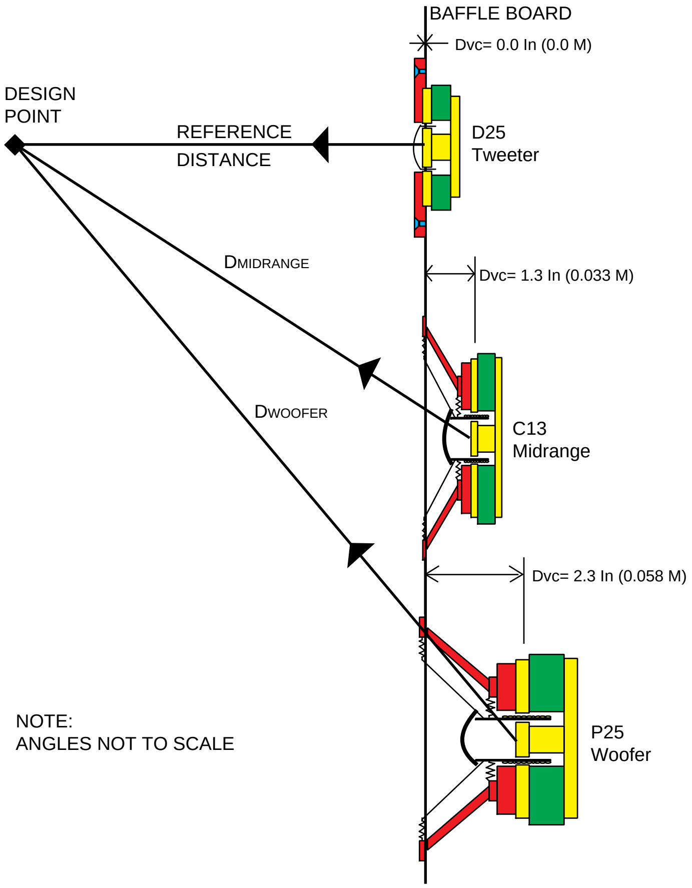


Tweeter SPL Response

■ Relative Transducer Delay

To determine the actual time positions of each transducer, a *design point* in space must be selected. Unless all of the transducers in a multiway acoustic system are coaxial mounted, an ideal crossover can only be designed for a single point in space. The drawing below illustrates the situation.

We know the acoustic response for each transducer, relative to their acoustic origins, but we must also determine any differences in delay.



At high frequencies, the acoustic origin of each transducer is very near the voice coil. This is where the conversion from electrical to acoustic wave propagation takes place.

The Tweeter is used as the reference since its voice coil is nearly in the plane of the baffle board. We will also assume the Design Point is on-axis with the Tweeter, and that the original SPL response for each driver was measured at the Design Point.

The voice coil of the Midrange driver is back set 0.033M and the Woofer is back set 0.058M.

However the total path difference between the drivers to the Design Point in space depends on the chosen reference distance, and the vertical spacing between the drivers.

At very far distance, the vertical driver spacing is relatively unimportant, and the path difference between the drivers becomes equal to the voice coil offsets. At closer distances the vertical driver spacing must be included in path computations.

Typical reference distances are usually given as either 1 or 2 Meters for most loudspeaker products. For this example we shall use 1 Meter as the reference distance. We shall also assume that the vertical spacing between each driver is about 6 Inches, or 0.15 Meters.

Using basic trig the acoustic path distances are:

$D_{TWEETER} = 1$ Meter
$D_{MIDRANGE} = \mathrm{sqrt}(\ (1+0.033)^2 + 0.15^2\ ) = 1.044$ Meter
$D_{WOOFER} = \mathrm{sqrt}(\ (1+0.058)^2 + 0.30^2\ ) = 1.100$ Meter

Therefore the Midrange and Woofer path delay differences are:

$\Delta D_{MIDRANGE} = 0.044$ Meter $T_{MIDRANGE} = 126$u Sec
$\Delta D_{WOOFER} = 0.100$ Meter $T_{WOOFER} = 286$u Sec
(Note: Speed of Sound constant 350M/Sec)

The Midrange acoustic response will be delayed by 126u Sec, and the Woofer will be delayed by 286u Sec. These delays must be included as the complete acoustic response for each section.

■ Crossover Transfer Functions

We will begin by determining the F/Q parameters for all of the transfer function blocks needed. Since a 4th order crossover will be built, the Butterworth 6dB Allpole family will be used as a target. This family has a response which is 6dB down at the corner, and even order LP/HP sections sum to a flat response. However, it is merely a starting point since later optimization will change the values.

For the Woofer section, a 4th order Lowpass is required. Using the **Analog | Allpole** dialog with a corner frequency 200Hz, the transfer function blocks are:

- LP2: F=200.0, Q=0.707
- LP2: F=200.0, Q=0.707

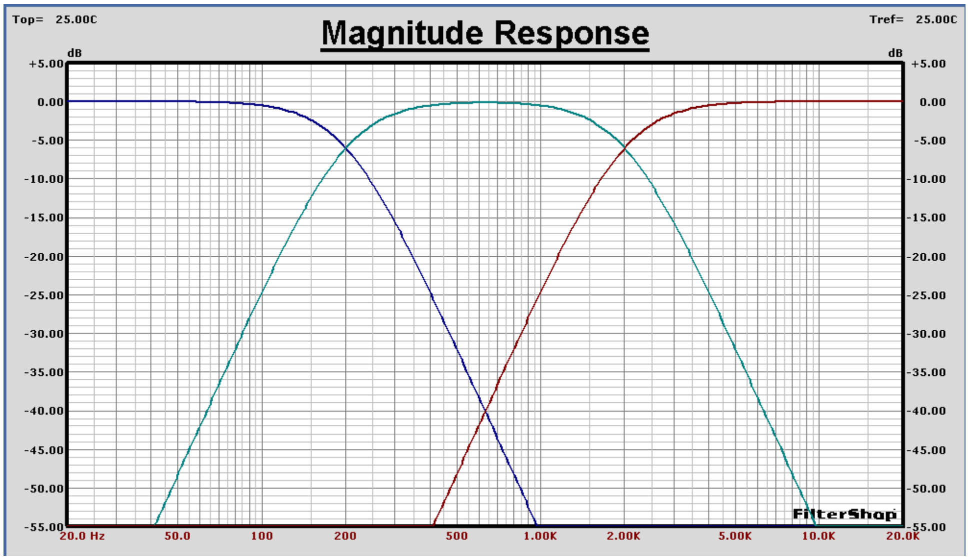
For the Midrange section, a 4th order Bandpass from 200Hz to 2kHz is required. This could be realized using either BP blocks or LP/HP blocks. Since we will probably wish to construct the final circuitry using all LP/HP filters, this form will be used here. The transfer function blocks are:

- HP2: F=200.0, Q=0.707
- HP2: F=200.0, Q=0.707
- LP2: F=2000.0, Q=0.707
- LP2: F=2000.0, Q=0.707

For the Tweeter section, a 4th order Highpass is required with a corner frequency of 2000Hz. The transfer function blocks are:

- HP2: F=2000.0, Q=0.707
- HP2: F=2000.0, Q=0.707

A system frequency range of 20Hz-20kHz will be used. The graph on the following page shows the response for each of the three crossover sections.



Transfer Function Optimization

If the response from each of the three transducers were perfectly flat, the transfer function block parameters just obtained would be the final values. However, the response of each transducer is not flat and the crossover functions must be altered to produce the best possible system response.

To accomplish this we would like to optimize their parameters by incorporating the actual response of the transducers. The SPL response of the transducers must be multiplied into the crossover filters, and then optimized against the ideal crossover targets. The Target system only generates purely analytic functions, and therefore cannot be used with an arbitrary response.

The easiest way to handle this task is by *generic transfer function modeling* in the circuit system. We are not interested in working with the actual circuits yet, but rather with the fundamental F/Q parameters in generic block form. Generic optimization is much faster since detailed circuitry is avoided.

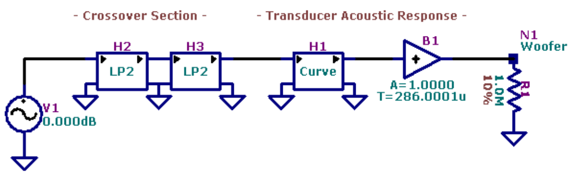
Using this technique we can quickly optimize the F/Q values of each crossover section with the actual response of each transducer. Once we have the final F/Q values, the needed circuit realizations can then be produced.

■ Woofer Section Optimization

We now start a new design file for the Woofer, and setup a circuit which includes both the generic crossover transfer function and the woofer acoustic response. The Transfer Function component (H) is very powerful for this kind of generic modeling, and provides both analytic and arbitrary response capability.

The circuit below shows three H components as well as a Buffer component. The Woofer's SPL response is imported into a Guide Curve, and then that arbitrary response is loaded in H1. B1 is used to represent the acoustic delay of the Woofer at 286u Sec. Therefore H1, B1 form the acoustic response of the Woofer.

The H2, H3 components are setup as LP2 blocks with the parameters Fp=200Hz and Q=0.707. They form the 4th order crossover Lowpass section.

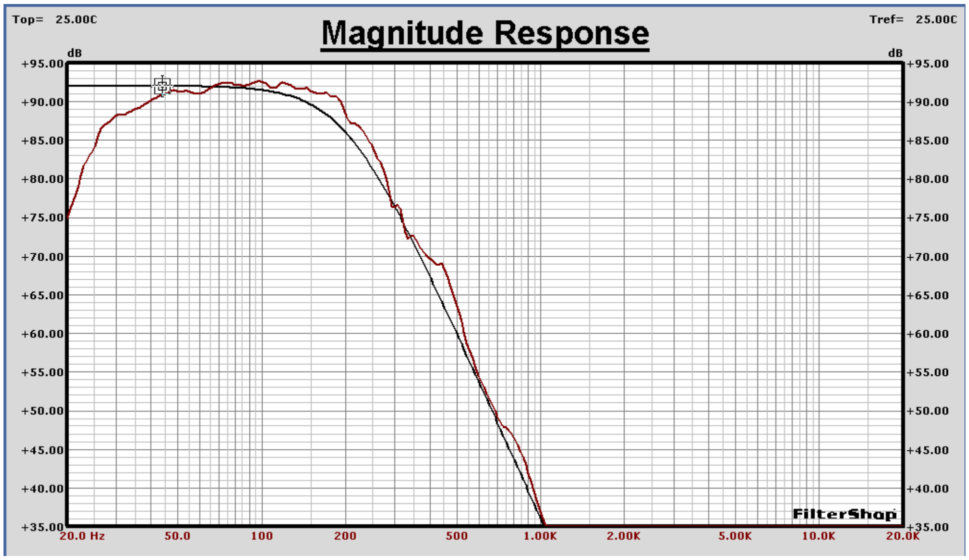


A base line flat level must now be chosen for the design. For the case of active crossovers, this can be almost anything since gain/padding differences for any crossover section can be produced. However it is best to choose one of the sections as a reference, and assume zero gain change for that section.

Looking at the previous SPL response curves, the Midrange and Tweeter both have higher output then the Woofer. If we wish to avoid adding extra gain in any of the sections, we must set the flat line level using the Woofer's response. A base level of 92dB would seem suitable for the design.

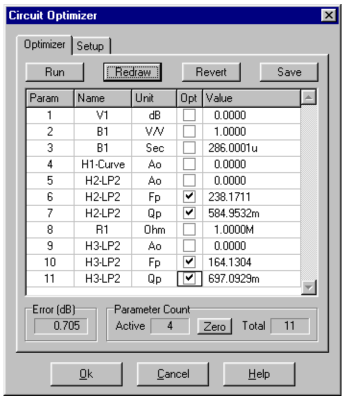
The previous crossover target functions were at a level of zero dB. The crossover target Guide Curves are copied to new Guide Curve entries, and then scaled up by 92dB. These will now become the optimization objectives.

The graph on the next page shows the response of the generic Woofer circuit, along with the new 92dB ideal optimizer objective.



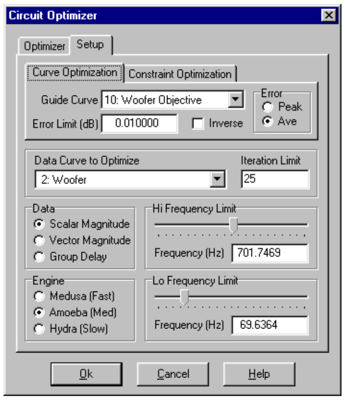
We are now ready to optimize the Woofer crossover section. The frequency range for optimization will be 70Hz to 700Hz. This covers most of the knee of the Lowpass response. Four parameters are selected for optimization: the two Fp and Qp values for both LP2 blocks H2, H3. The optimizer setup is shown below.

After optimization, the Magnitude graph on the following page is produced.

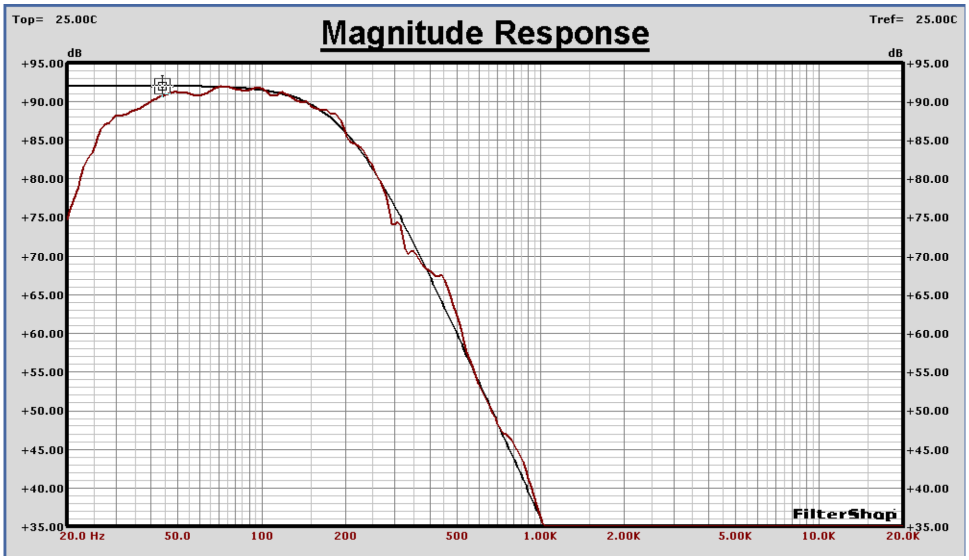

Circuit Optimizer

Param	Name	Unit	Opt	Value
1	V1	dB	☐	0.0000
2	B1	V/V	☐	1.0000
3	B1	Sec	☐	286.0001u
4	H1-Curve	Ao	☐	0.0000
5	H2-LP2	Ao	☐	0.0000
6	H2-LP2	Fp	☑	238.1711
7	H2-LP2	Qp	☑	584.9532m
8	R1	Ohm	☐	1.0000M
9	H3-LP2	Ao	☐	0.0000
10	H3-LP2	Fp	☑	164.1304
11	H3-LP2	Qp	☑	697.0929m

Error (dB) 0.705
Parameter Count: Active 4 Total 11


Circuit Optimizer

Guide Curve: 10: Woofer Objective
Error Limit (dB): 0.010000
☐ Inverse
Error: ○ Peak ● Ave
Data Curve to Optimize: 2: Woofer
Iteration Limit: 25
Data: ● Scalar Magnitude ○ Vector Magnitude ○ Group Delay
Hi Frequency Limit: Frequency (Hz) 701.7469
Engine: ○ Medusa (Fast) ● Amoeba (Med) ○ Hydra (Slow)
Lo Frequency Limit: Frequency (Hz) 69.6364



The response is now very close to the ideal Butterworth-6dB objective. The changes to the Fp and Qp values can be obtained by opening the editing dialog on both of the H2, H3 components. The parameter values are now:

- LP2: F= 238.1711, Q= 0.5849
- LP2: F= 164.1304, Q= 0.6970

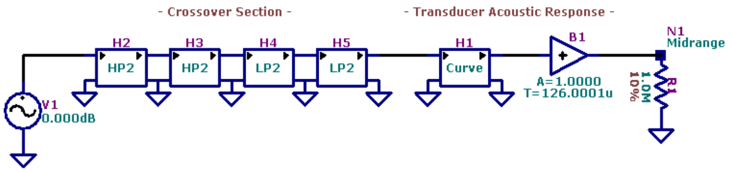
The crossover filters for this section have now been optimized to yield the best *combined* response by including the transducer's acoustic response. We can now repeat this process for the Midrange and Tweeter.

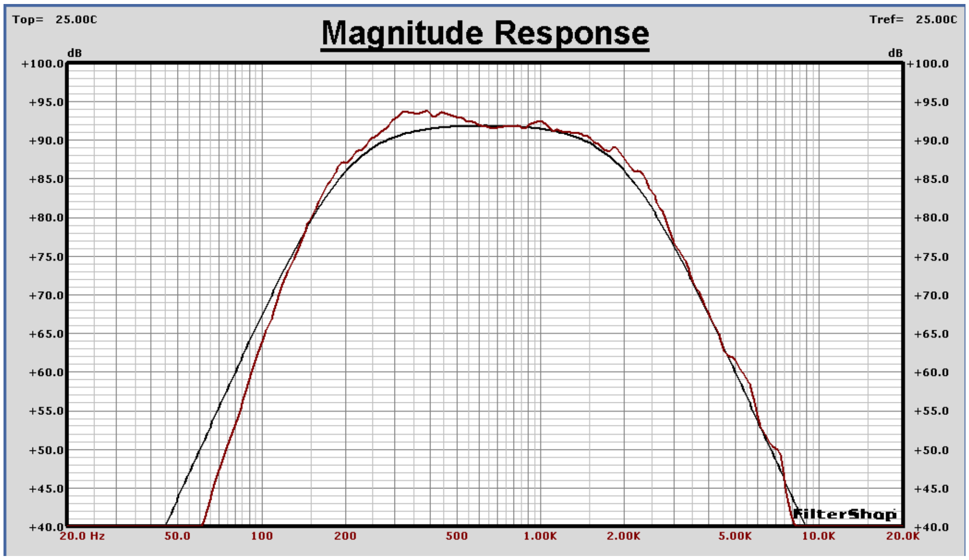
■ Midrange Optimization

Another design file is started (or copied and renamed from the previous) and edited to construct the Midrange simulation. For the Midrange crossover, four H blocks will be used and setup with the ideal target parameters previously determined: 2xHP2:F=200,Q=0.707, and 2xLP2:F=2K,Q=0.707.

The Midrange SPL response is imported and then loaded into the H1 component, and the Buffer delay is now set to 126u Sec. The resulting circuit is shown below.

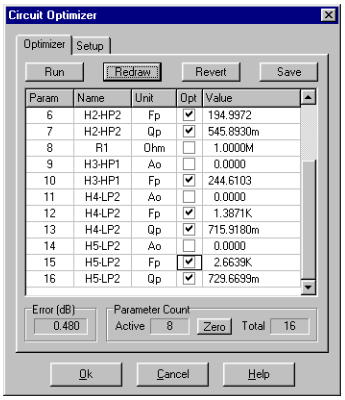
The response of the circuit as compared to the ideal target objective is also shown below in the Magnitude graph.





The frequency range for optimization this time is about 70Hz to 6kHz, which covers enough of the slopes of each side to hold the order. This time nine parameters will be optimized: the four Fp values, the four Qp values, and an Ao value.

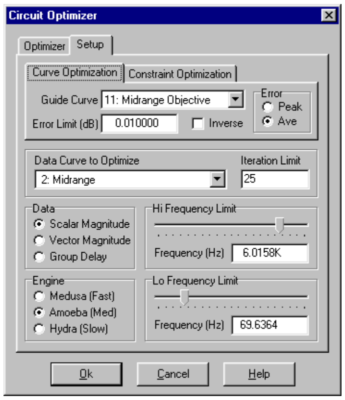
These parameters are all in the H2-H5 components of course. The Ao parameter is enabled for H2. We only need to have a single gain parameter enabled for optimization, to provide overall shelving flexibility. After the optimization, the Magnitude graph below displays the results.



Param	Name	Unit	Opt	Value
6	H2-HP2	Fp	☑	194.9972
7	H2-HP2	Qp	☑	545.8930m
8	R1	Ohm	☐	1.0000M
9	H3-HP1	Ao	☐	0.0000
10	H3-HP1	Fp	☑	244.6103
11	H4-LP2	Ao	☐	0.0000
12	H4-LP2	Fp	☑	1.3871K
13	H4-LP2	Qp	☑	715.9180m
14	H5-LP2	Ao	☐	0.0000
15	H5-LP2	Fp	☑	2.6639K
16	H5-LP2	Qp	☑	729.6699m

Error (dB) 0.480

Parameter Count: Active 8 Zero Total 16



Guide Curve: 11: Midrange Objective

Error Limit (dB): 0.010000

☐ Inverse

Error: ○ Peak ● Ave

Data Curve to Optimize: 2: Midrange

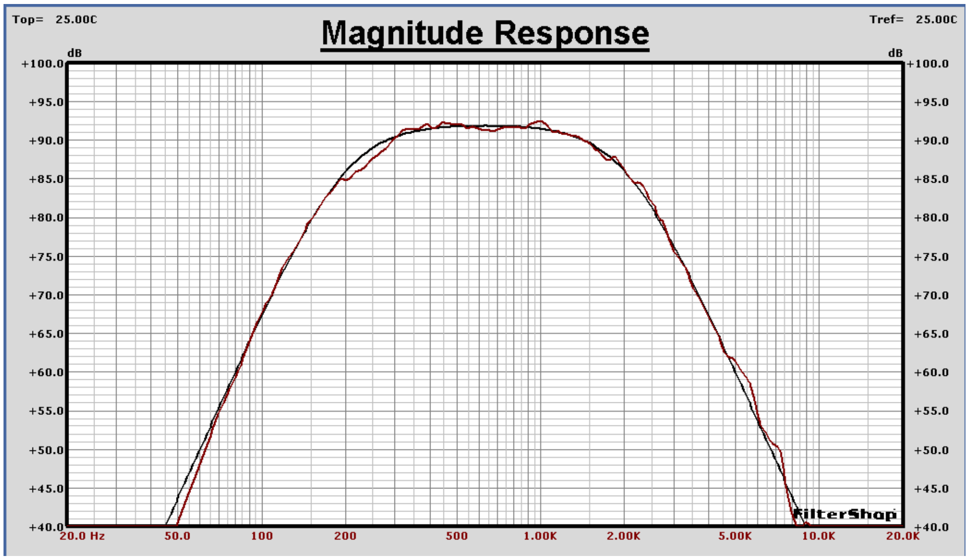
Iteration Limit: 25

Data: ● Scalar Magnitude ○ Vector Magnitude ○ Group Delay

Hi Frequency Limit: Frequency (Hz) 6.0158K

Engine: ○ Medusa (Fast) ● Amoeba (Med) ○ Hydra (Slow)

Lo Frequency Limit: Frequency (Hz) 69.6364



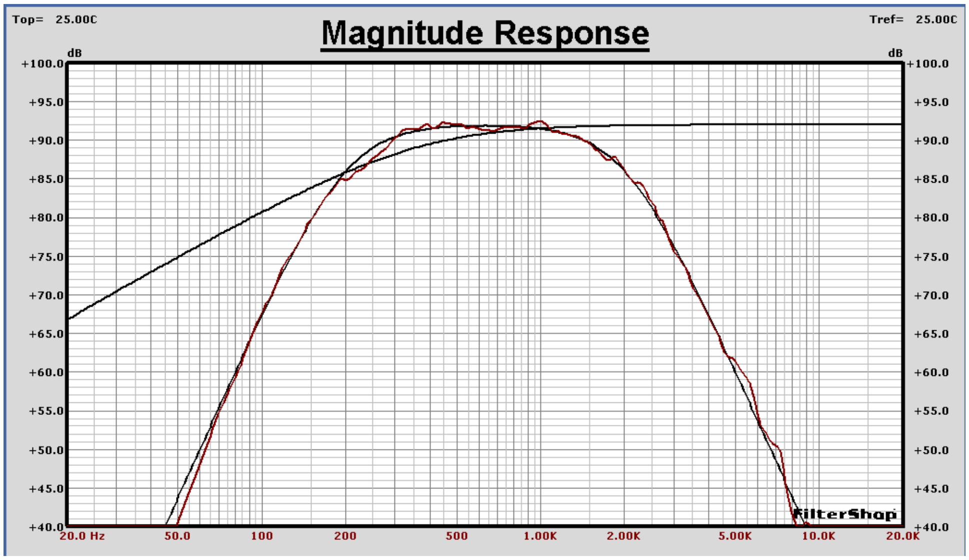
Upon inspection of the optimized H2-H5 parameters, we obtain:

- HP2: F= 167.6035, Q= 0.6070, A= +1.0790dB
- HP2: F= 43.0414, Q= 0.1176
- LP2: F= 1.5170K, Q= 0.7401
- LP2: F= 2.6115K, Q= 0.5921

These results are quite interesting. Since the overall level of the previous response was actually higher then the objective, we would have expected the gain parameter to probably show a negative result, in order to drop the overall curve. However the new value turned out to be +1.08dB.

Now note the F and Q values for the second HP2 block. The corner frequency has been moved down to 43Hz (from 200Hz), and the Q value has dramatically dropped to 0.12 (from 0.707). All other parameters show normal change.

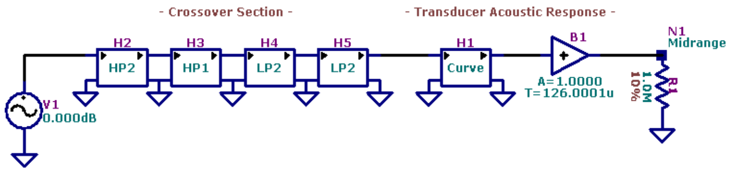
Since one of the HP2 blocks has been substantially changed, it is a good idea to plug these parameters into the Target System, and see what this response looks like by itself. Therefore, we setup a single TFB as HP2 with Fp=43 and Qp=0.12. Since we are up at the 92dB level, we set the offset to 92dB. The response is shown below. Essentially it is a 1st order Highpass function.

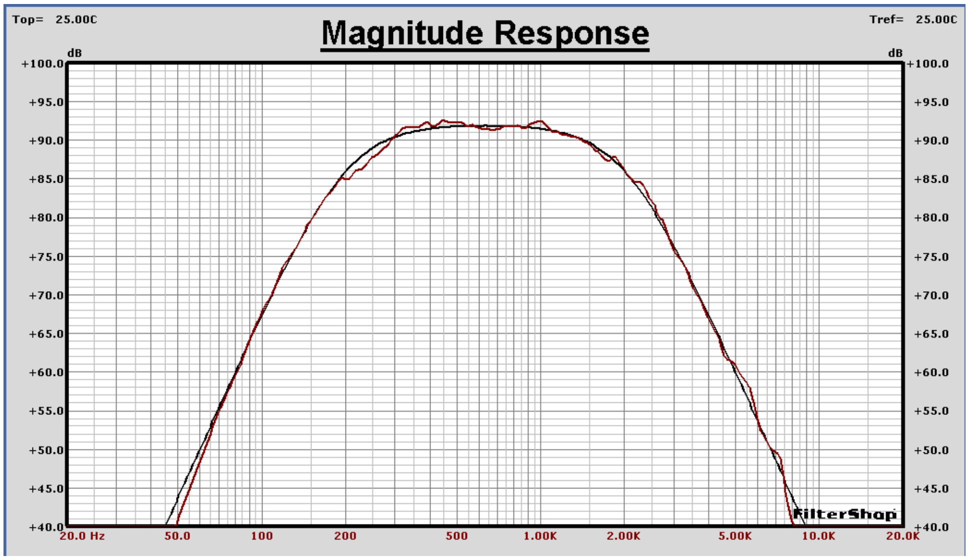


Therefore, the optimizer has informed us that the HP2 block is unnecessary, and all we need is an HP1. The H3 block is now changed to an HP1 filter, and the Fp value set back to 200Hz. This time, we will only be optimizing eight parameters since the Qp value of H3 is no longer used. The results are shown below:

- HP2: F= 194.9972, Q= 0.546, A= +0.840dB
- HP1: F= 244.6103
- LP2: F= 1.3871K, Q= 0.716
- LP2: F= 2.6639K, Q= 0.730

So, the crossover section for this Midrange section will be HP3/LP4.



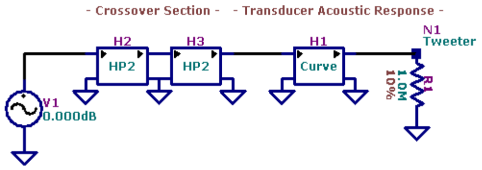


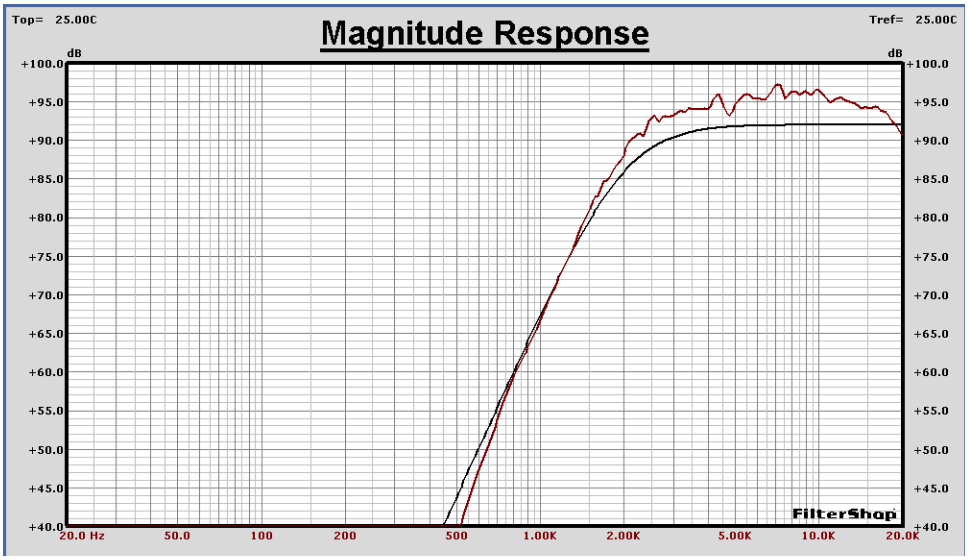
Tweeter Optimization

Another design file is started (or copied and renamed from the previous) and edited to construct the Tweeter simulation. For the Tweeter crossover, two H blocks will be used and setup with the ideal target parameters previously determined: 2xHP2:F=2k,Q=0.707.

The Tweeter SPL response is imported and then loaded into the H1 component. There is no extra delay for the Tweeter, since it was our reference. The resulting circuit is shown below.

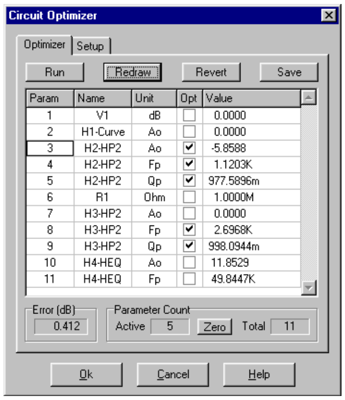
The response of the circuit as compared to the ideal target objective is also shown below in the Magnitude graph.





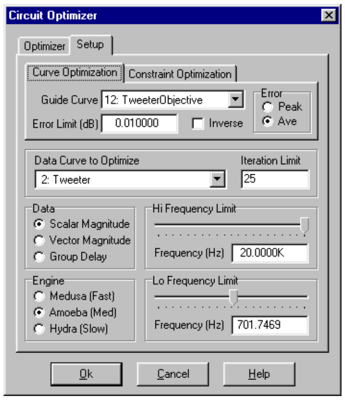
The frequency range for optimization this time is about 700Hz to 20kHz, which covers the major portion of the transition band and passband of the Highpass function. This time five parameters will be optimized: the two Fp values, the two Qp values, and an Ao value.

These parameters are all in the H2-H3 components of course. The Ao parameter is enabled for H2. We only need to have a single gain parameter enabled for optimization, to provide overall shelving flexibility. After the optimization, the Magnitude graph below displays the results.

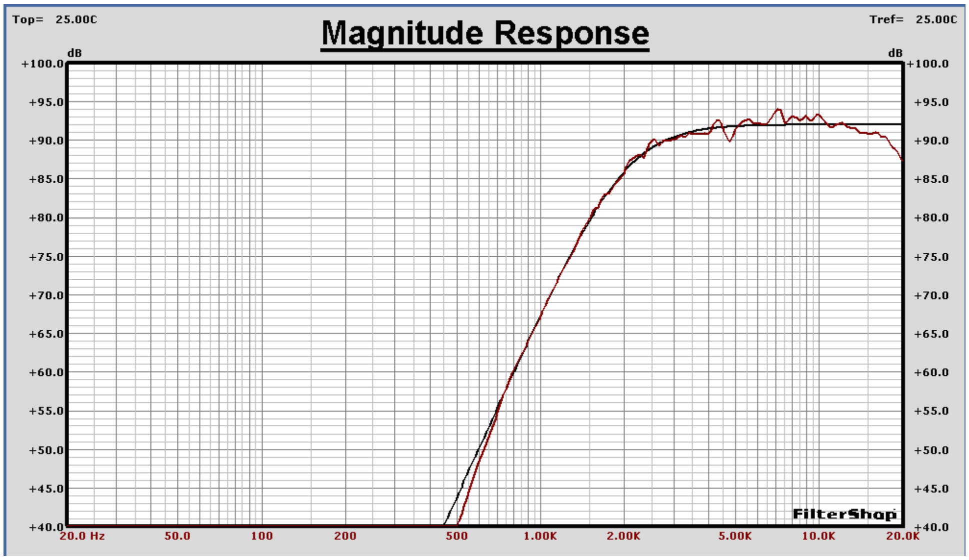


Param	Name	Unit	Opt	Value
1	V1	dB	☐	0.0000
2	H1-Curve	Ao	☐	0.0000
3	H2-HP2	Ao	☑	-5.8588
4	H2-HP2	Fp	☑	1.1203K
5	H2-HP2	Qp	☑	977.5896m
6	R1	Ohm	☐	1.0000M
7	H3-HP2	Ao	☐	0.0000
8	H3-HP2	Fp	☑	2.6968K
9	H3-HP2	Qp	☑	998.0944m
10	H4-HEQ	Ao	☐	11.8529
11	H4-HEQ	Fp	☐	49.8447K

Error (dB) 0.412
Parameter Count: Active 5 Zero Total 11



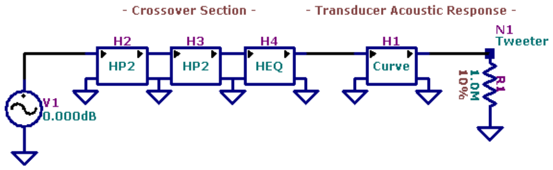
Guide Curve 12: TweeterObjective
Error Limit (dB) 0.010000
☐ Inverse
Error: ○ Peak ● Ave
Data Curve to Optimize 2: Tweeter
Iteration Limit 25
Data: ● Scalar Magnitude ○ Vector Magnitude ○ Group Delay
Hi Frequency Limit: Frequency (Hz) 20.0000K
Engine: ○ Medusa (Fast) ● Amoeba (Med) ○ Hydra (Slow)
Lo Frequency Limit: Frequency (Hz) 701.7469

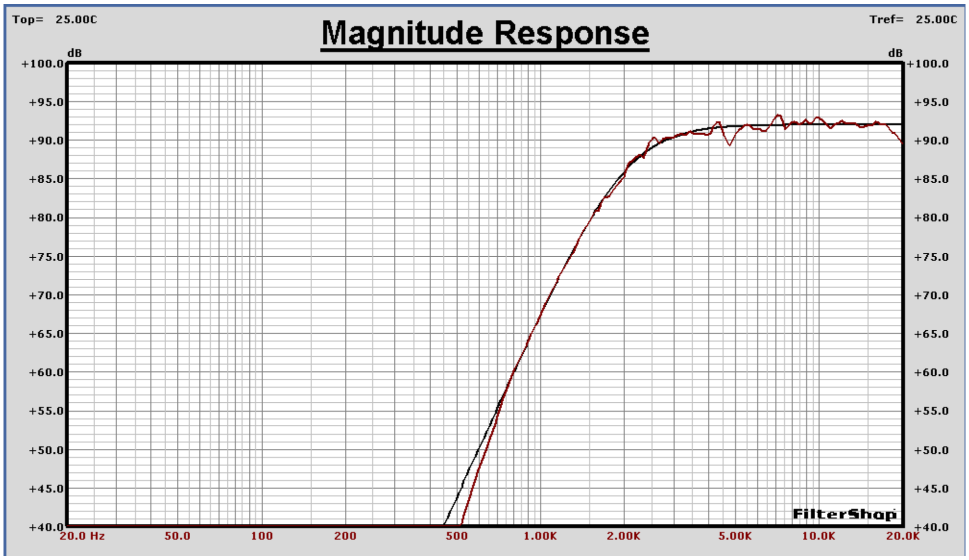


While the newly optimized response is much closer to the ideal objective, the region near 20kHz is rolling off. If we wish to correct the response of the Tweeter at these high frequencies, we could add an HEQ block and optimize it as well. Two additional parameters will now be optimized, the Ao and Fp values for the HEQ block. The starting values of A=6dB and Fp=20kHz will be used. After optimization, the results are shown below.

- HP2: F= 1.12K, Q= 0.978, A= -5.8588dB
- HP2: F= 2.70K, Q= 0.998
- HEQ: F= 49.85K, A= 11.85dB

This is now a flatter response in the high frequency region. We could further adjust this manually later to provide any level of Tweeter boost desired.





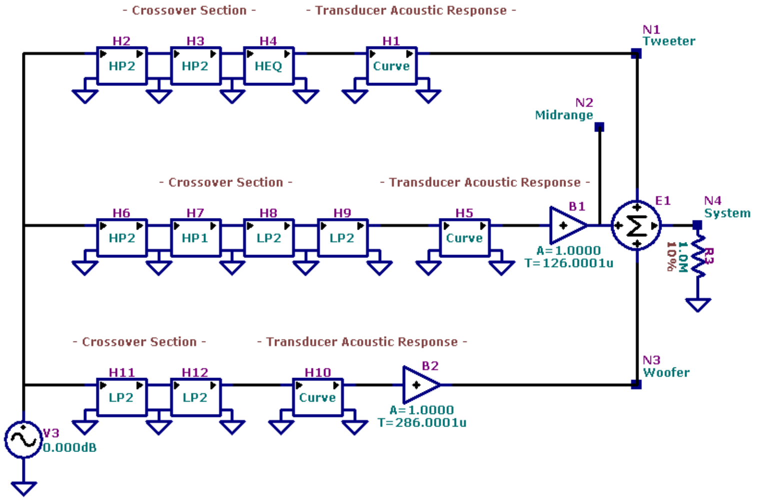
■ System Optimization

We are now ready to simulate the total system response. A new design file is opened and all three of the previous circuits are imported. The inputs are paralleled to use a common single generator, with the two extra generators removed.

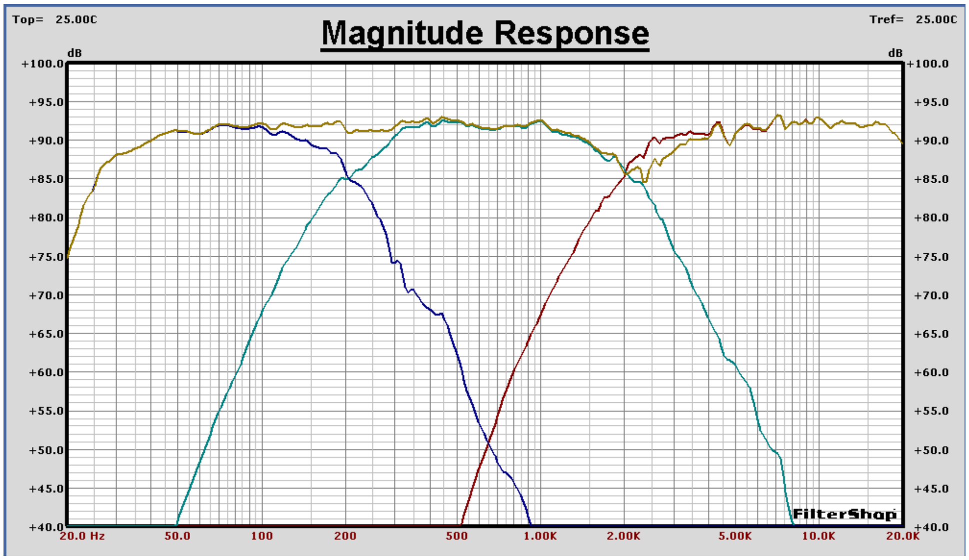
A summer component is added to sum the outputs of the Woofer, Midrange, and Tweeter networks. A new Data Node is added for the main system output. The new system circuit model is shown below.

Initially all of the outputs will be summed inphase. The first graph on the following page displays the response for each output as well as the system output. The lower crossover point at 200Hz between the Woofer-Midrange has filled in nicely. However the higher crossover point at 2kHz between the Midrange-Tweeter shows a significant dip.

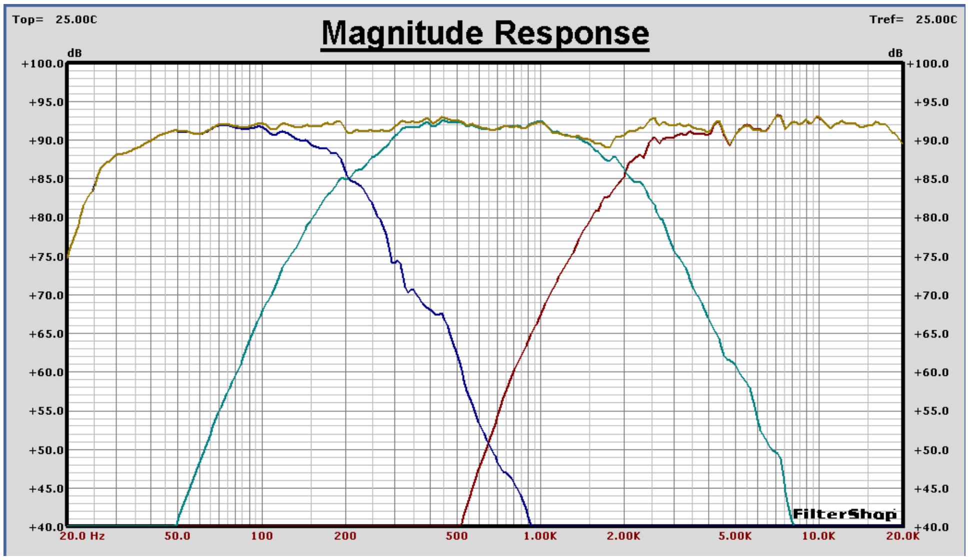
The obvious conclusion would be that the Tweeter polarity must be reversed. By changing the polarity on the top input of the Summer component, the response in the lower graph is produced. The crossover region at 2kHz is now correct.



System Response, All Outputs Same Polarity



System Response, Tweeter Polartity Reversed



We now examine only the main system output as compared to a flat line Target of 92dB. This is shown on the next page. The response is approximately -3dB @ 35Hz and 20kHz. The response has a flatness of ±2dB across the entire spectrum.

By previously optimizing the individual sections alone, the summed response is already very good. There is little room for improvement, however the dip at the 2kHz crossover region can be somewhat reduced.

To flatten the upper crossover point, we could elect to reoptimize the tweeter blocks, or the Midrange blocks. In this case the Midrange section was chosen, and a frequency range of 100Hz to 4kHz was setup.

Eight parameters were optimized in blocks H6-H9: Ao/Fp/Qp, Fp, Fp/Qp, and Fp,Qp. These represent the HP3/LP4 Bandpass filter with shelving gain.

The results are shown in the top graph on the next page. A small dip remains in the 5kHz region, so we will reoptimize the Tweeter section again. This time the frequency range is 1kHz to 16kHz. Five parameters are enabled: Ao/Fp/Qp and Fp/Qp in the H2, H3 blocks. The results are shown in the bottom graph.

The final crossover filter parameters are:

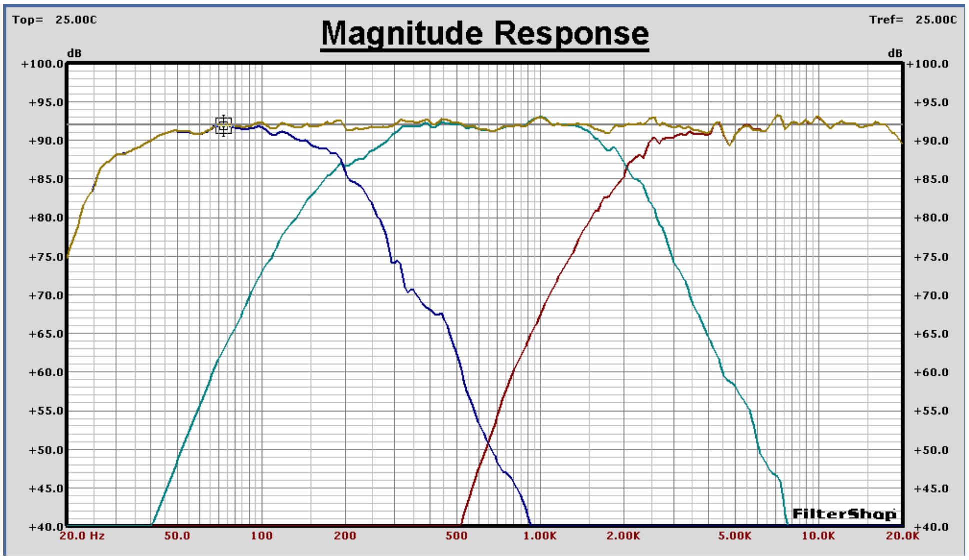
Woofer Section:
  - LP2: F= 238.17, Q= 0.5849
  - LP2: F= 164.13, Q= 0.6970

Midrange Section:
  - HP2: F= 116.16 , Q= 0. 4696, A= -0.33dB
  - HP1: F= 208.92
  - LP2: F= 2.1125K, Q= 0.6908
  - LP2: F= 1.5627K, Q= 0.9605

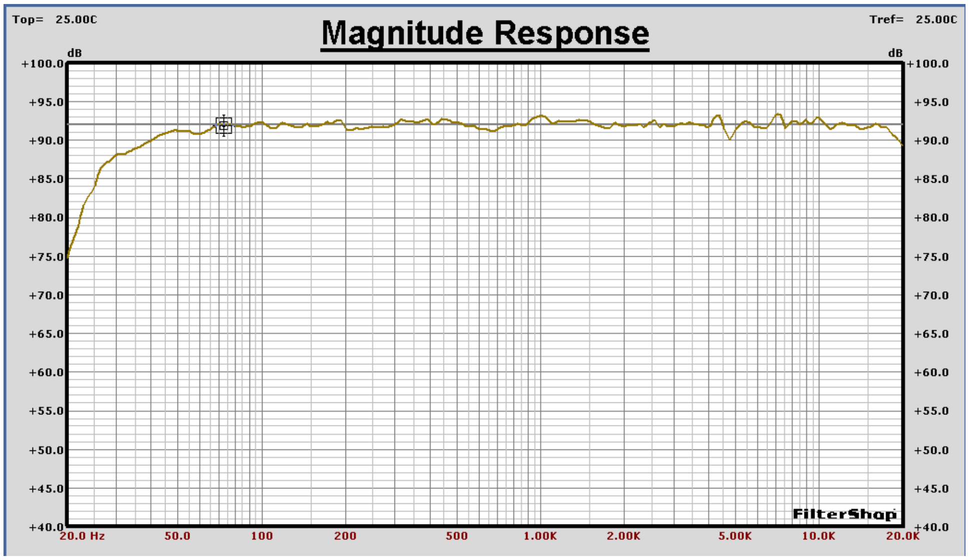
Tweeter Section:
  - HP2: F= 1.6100K, Q= 1.1494, A= -6.22dB
  - HP2: F= 3.1324K, Q= 1.1277
  - HEQ: F= 49.85K, A= 11.85dB

With these design parameters all of the necessary circuit realizations can now be quickly produced, primarily using synthesis only.

System Response, After Midrange Reoptimization



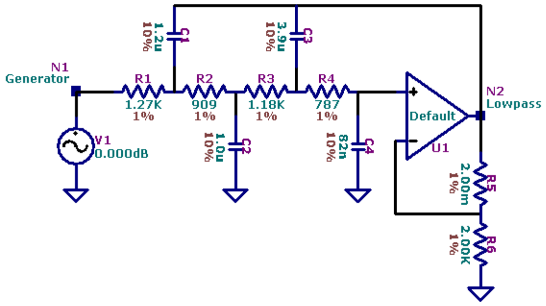
System Response, After Tweeter Reoptimization



■ Woofer Circuit Design

We need to produce a 4th order Lowpass filter. Since the Q values are relatively low, we might be able to get away with a single stage Sallen-Key 4th order design.

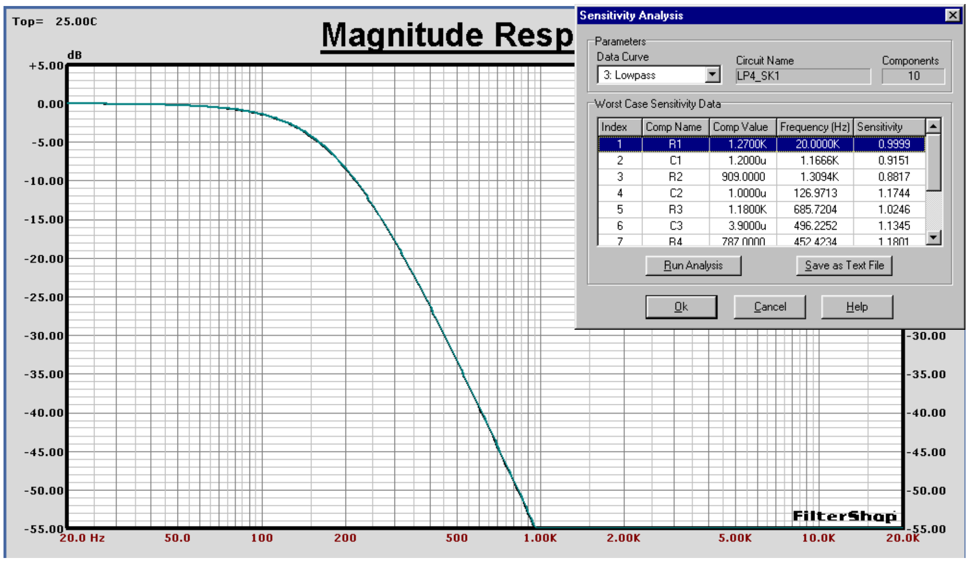
Another design file is started for this circuit design, and the Target system is setup with two TFBs, each using the parameters from the H11, H12 circuit blocks. The LP4_SK1 circuit is loaded. The capacitor precision is changed to 10% to limit the standard values.



Since we would like to obtain unity gain from the circuit, Synthesis is run using gain of 1.000001 and resistor values of 1K, 2K.

The circuit schematic and response is shown below. The response is right on top of the target. We can check the reliability of the design easily by running the sensitivity analysis. This is also shown below.

The results are excellent. All of the S values are below 1.5. Extremely stable. R5 will be replaced by a wire, and R6 will be removed.



Parameters

Data Curve: 3: Lowpass

Circuit Name: LP4_SK1

Components: 10

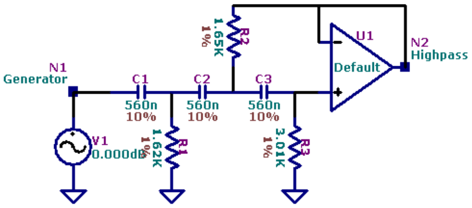
Worst Case Sensitivity Data

Index	Comp Name	Comp Value	Frequency (Hz)	Sensitivity
1	R1	1.2700K	20.0000K	0.9999
2	C1	1.2000u	1.1666K	0.9151
3	R2	909.0000	1.3094K	0.8817
4	C2	1.0000u	126.9713	1.1744
5	R3	1.1800K	685.7204	1.0246
6	C3	3.9000u	496.2252	1.1345
7	R4	787.0000	452.4234	1.1801

■ Midrange Circuit Design

For this section an HP3 and LP4 filter combination is needed. Again we shall try a 4th order single section Lowpass, and also a 3rd order single section Highpass.

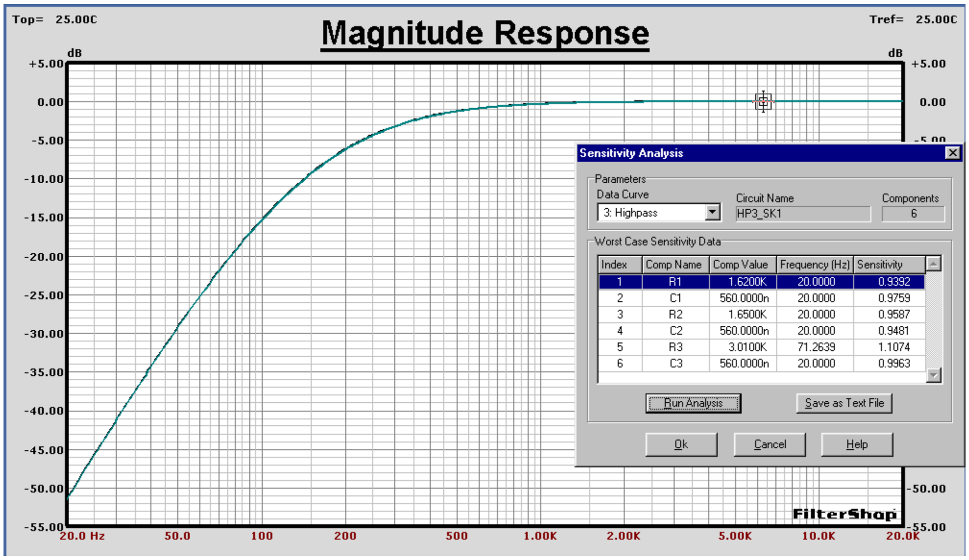
Another design file is started for this circuit design, and the Target system is setup with four TFBs, each using the parameters from the H6 - H9 circuit blocks. Only two of the four TFBs will be enabled at any one time, since the two stages must be designed individually.



The HP3_SK1 circuit is loaded. The capacitor precision is changed to 10% to limit the standard values. Synthesis is run using preset resistor value of 2K.

The circuit schematic and response is shown below. The response is right on top of the target. We can check the reliability of the design easily by running the sensitivity analysis. This is also shown below.

Excellent results, all S values are below 1.1.



Parameters

Data Curve: 3: Highpass

Circuit Name: HP3_SK1

Components: 6

Worst Case Sensitivity Data

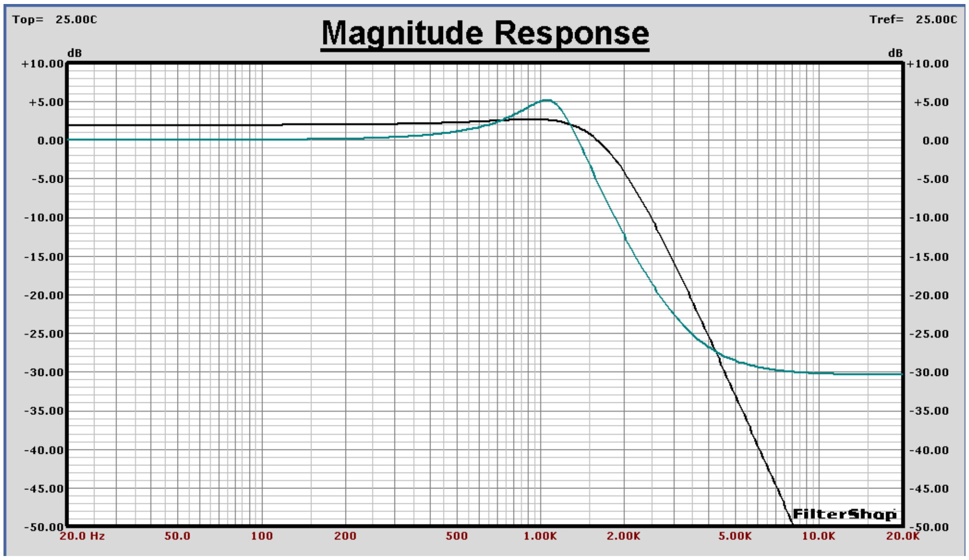
Index	Comp Name	Comp Value	Frequency (Hz)	Sensitivity
1	R1	1.6200K	20.0000	0.9392
2	C1	560.0000n	20.0000	0.9759
3	R2	1.6500K	20.0000	0.9587
4	C2	560.0000n	20.0000	0.9481
5	R3	3.0100K	71.2639	1.1074
6	C3	560.0000n	20.0000	0.9963

We save the design, and then resave it again as a different name to design the LP4 stage. We turn off the previous two HP TFBs, and enable the two LP TFBs representing H8, H9. The LP4_SK1 circuit is loaded. The capacitor precision is changed to 10% to limit the standard values.

Synthesis is run using a preset gain of 1.00001 and resistor values of 1K, 2K.

The circuit response is shown below. This design failed. Not even close to the target. Looking at the target it is obvious that there is higher Q involved, evident in the peaking near the knee of the response. It is probably impossible to produce this target while attempting to use unity gain.

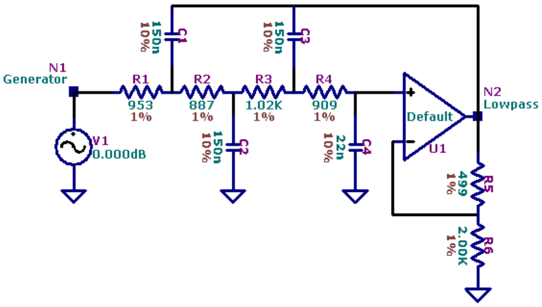
We can rerun synthesis again, but this time we will try a higher gain. Say, 1.25. The results are shown on the following page.

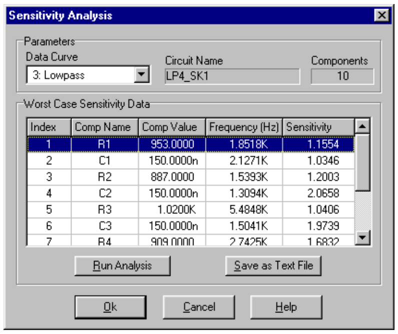


This looks much better. The response is right on top of the target. We can check the reliability of the design again by running the sensitivity analysis. This is also shown below.

The results are very good. The S values are generally 2 or less.

We need to combine both stages. However we now have an additional gain occurring in this stage, and the actual Midrange filter requires a loss of 0.329dB.





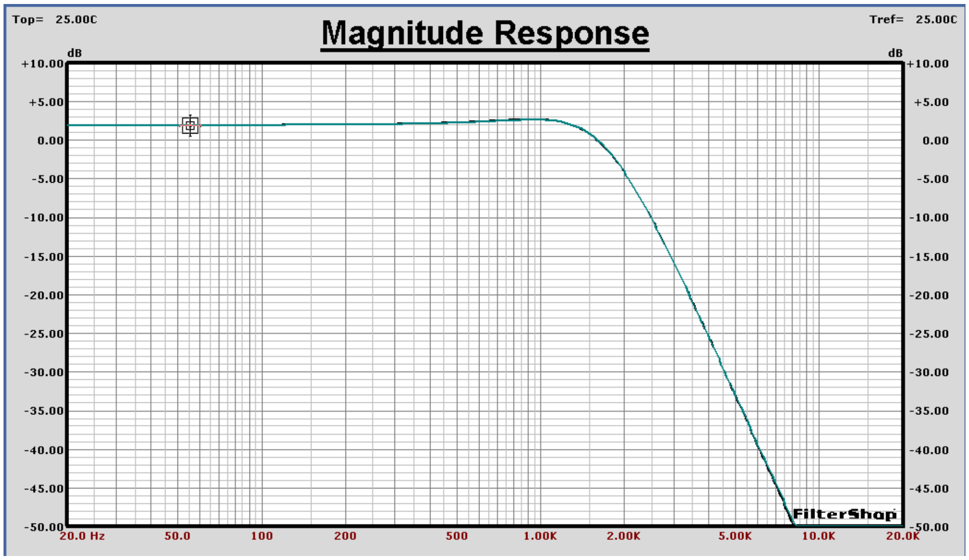
Data Curve: 3: Lowpass

Circuit Name: LP4_SK1

Components: 10

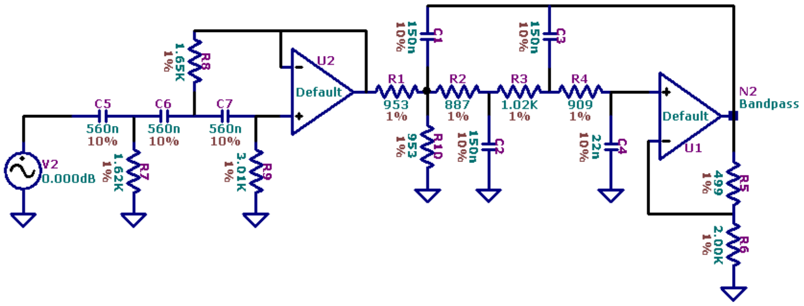
Worst Case Sensitivity Data

Index	Comp Name	Comp Value	Frequency (Hz)	Sensitivity
1	R1	953.0000	1.8518K	1.1554
2	C1	150.0000n	2.1271K	1.0346
3	R2	887.0000	1.5393K	1.2003
4	C2	150.0000n	1.3094K	2.0658
5	R3	1.0200K	5.4848K	1.0406
6	C3	150.0000n	1.5041K	1.9739
7	R4	909.0000	2.7425K	1.6832



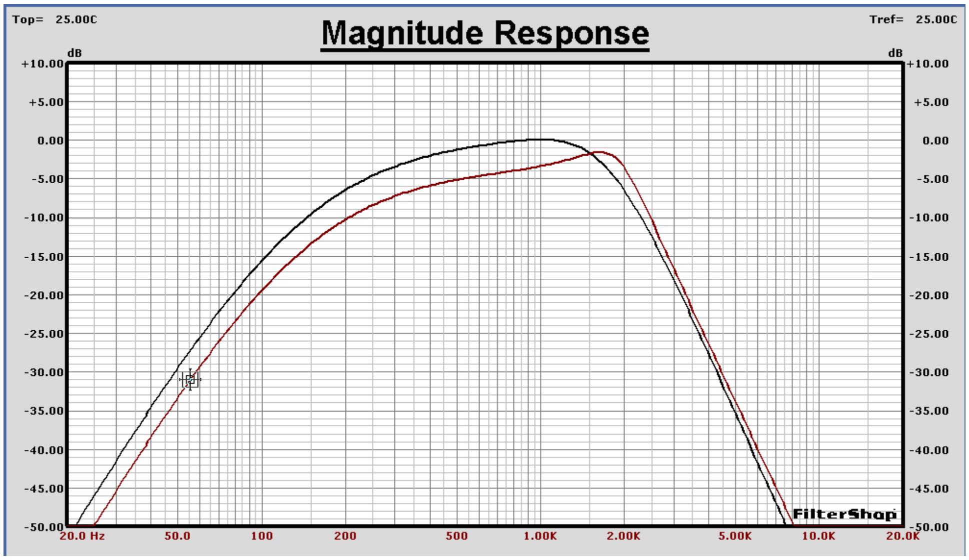
We save and resave the design file under a new name, change the circuit to custom, and import the previous circuit. We also enable the previous HP1/HP2 TFBs in the Target system, and set the Ao gain of one to -0.329dB.

The circuit is modified to cascade both of the stages together. We must provide some means to correct the overall gain of the circuit by adding some loss. One easy way this can be done is by splitting R1 into two resistors with the new resistor R10 connected to ground. Given the right values, a voltage divider is formed with the same impedance as the original R1. This is shown below.

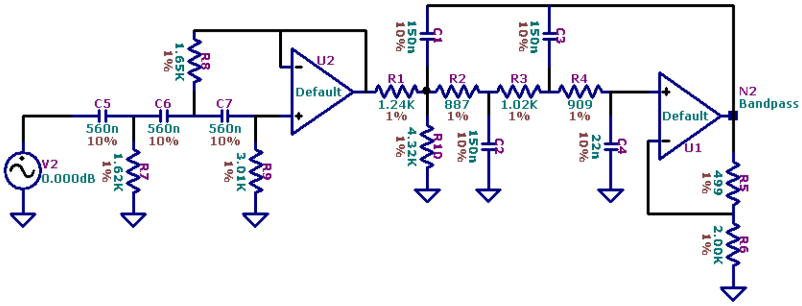


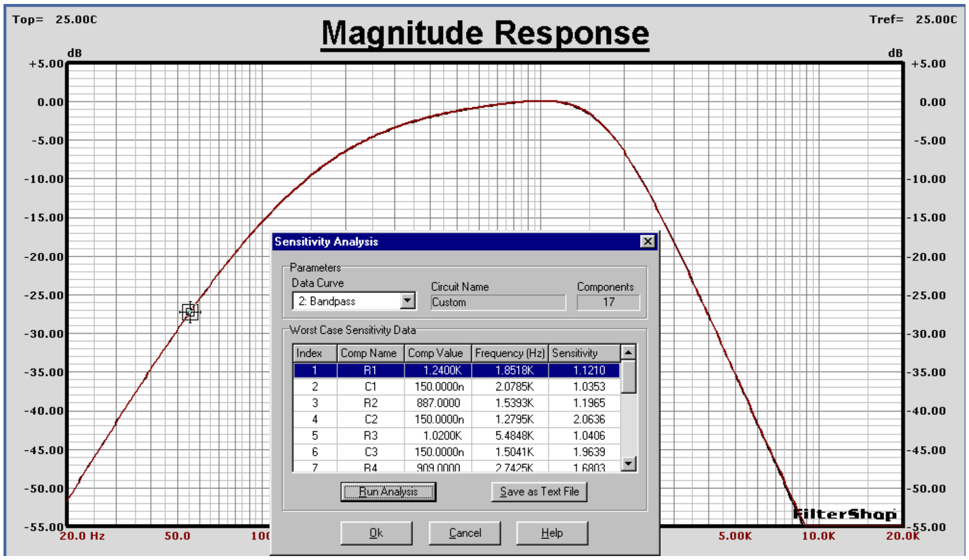
R1 is simply copied and the new R10 is connected to ground.

If the Target response is copied to a Guide Curve, we can run the optimizer to find the correct values for R1 and R10.



The results are shown below. The correct values for R1 and R10 are: 1.24K and 4.32K. The circuit response is now right on top of the target. Running the sensitivity analysis again shows little change, with all values typically below 2 which is very good.





Data Curve: 2: Bandpass
Circuit Name: Custom
Components: 17

Worst Case Sensitivity Data

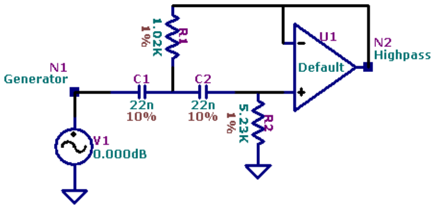
Index	Comp Name	Comp Value	Frequency (Hz)	Sensitivity
1	R1	1.2400K	1.8518K	1.1210
2	C1	150.0000n	2.0785K	1.0353
3	R2	887.0000	1.5393K	1.1965
4	C2	150.0000n	1.2795K	2.0636
5	R3	1.0200K	5.4848K	1.0406
6	C3	150.0000n	1.5041K	1.9639
7	R4	909.0000	2.7425K	1.6803

■ Tweeter Circuit Design

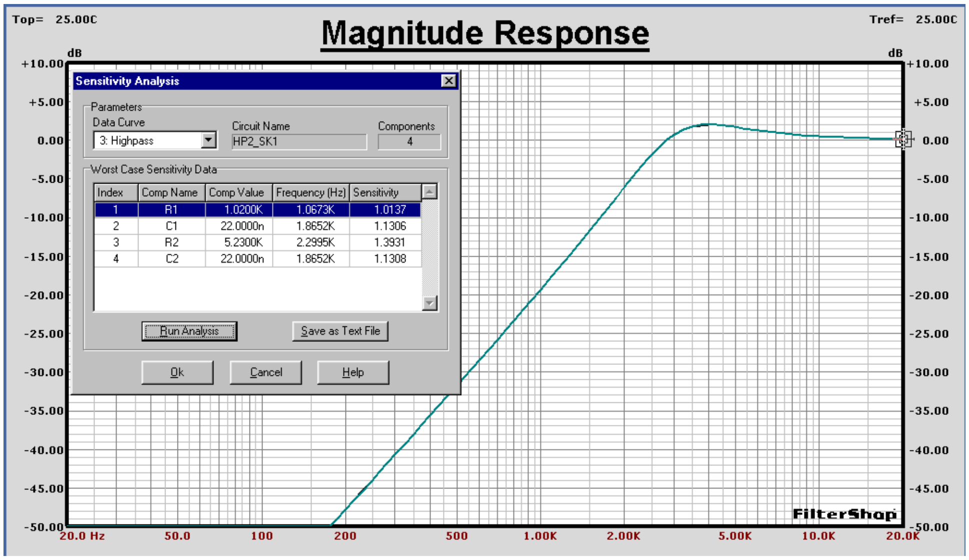
For this section an HP4 and HEQ filter combination is needed. In addition, the polarity must be reversed and the overall gain must be -6.25dB. The Q values for both of the HP2 blocks are much higher than the previous. Using a single stage would be impossible.

To handle all of the above requirements, a three stage design will be used. Two HP2_SK1 circuits will be used, along with an inverting stage which also provides the HEQ function.

The file is saved and then saved/renamed. The Target parameters for the Tweeter are setup, and the first HP2 TFB is enabled. The HP2_SK1 circuit is loaded. The capacitor precision is changed to 10% to limit the standard values. Synthesis is run using preset resistor value of 1K.



The circuit schematic and response is shown below. The response is right on top of the target. We can check the stability of the design easily by running the sensitivity analysis. This is also shown below. All S values are below 1.4 indicating excellent stability.



Parameters

Data Curve: 3: Highpass

Circuit Name: HP2_SK1

Components: 4

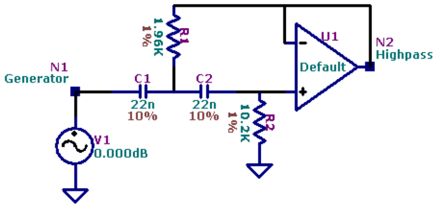
Worst Case Sensitivity Data

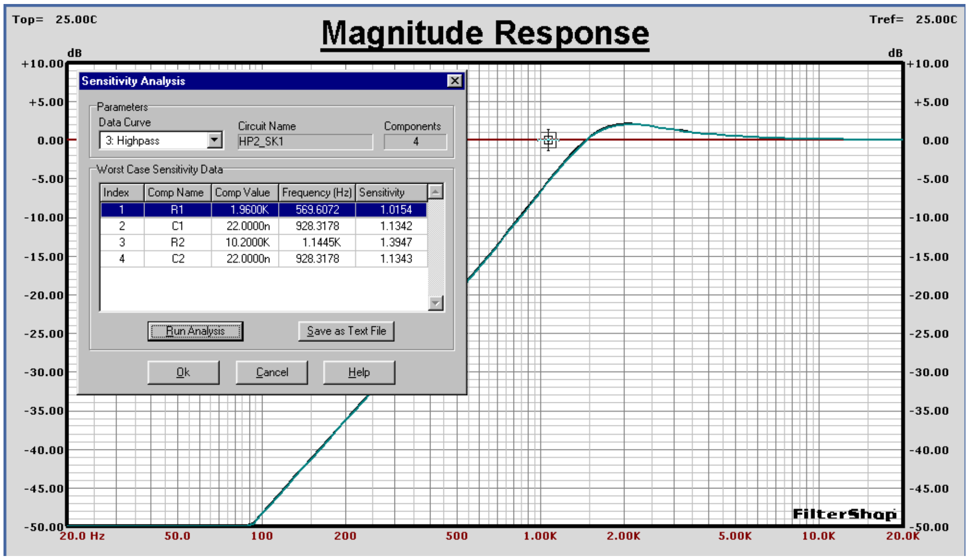
Index	Comp Name	Comp Value	Frequency (Hz)	Sensitivity
1	R1	1.0200K	1.0673K	1.0137
2	C1	22.0000n	1.8652K	1.1306
3	R2	5.2300K	2.2995K	1.3931
4	C2	22.0000n	1.8652K	1.1308

The file is saved and then resaved/renamed. The second HP2 TFB is enabled. Synthesis is run again using preset resistor value of 2K.

The circuit schematic and response is shown below. The results are very similar to the previous stage. Excellent sensitivity.

We are now ready to add the inverting HEQ stage, and append it to both of these HP2 stages. There are four components within the inverter, configured as an HEQ function. Three of the four will be optimized against the Tweeter crossover target, with the capacitor being held constant.





Parameters

Data Curve: 3: Highpass

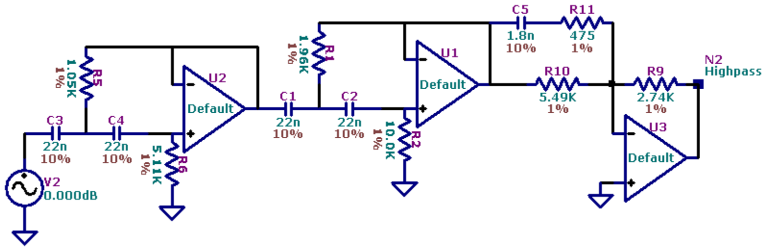
Circuit Name: HP2_SK1

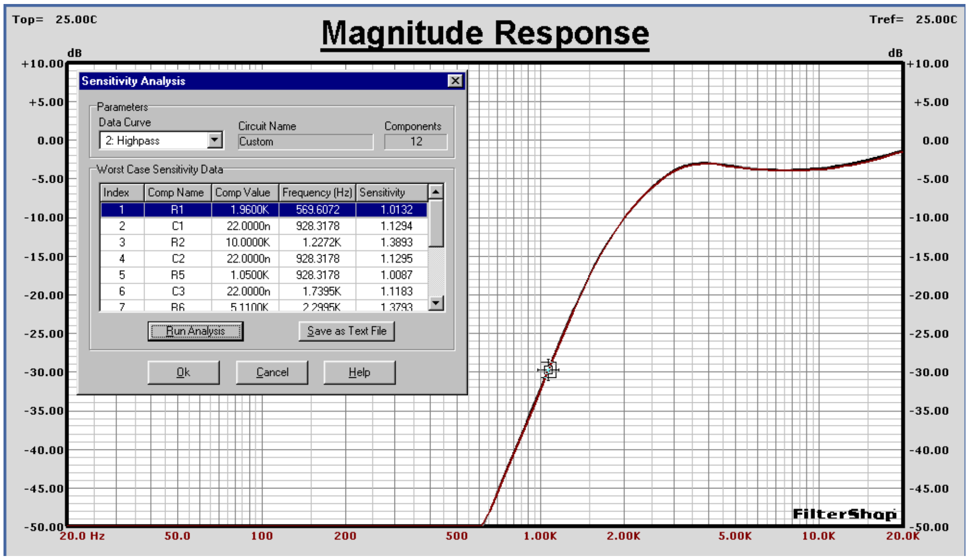
Components: 4

Worst Case Sensitivity Data

Index	Comp Name	Comp Value	Frequency (Hz)	Sensitivity
1	R1	1.9600K	569.6072	1.0154
2	C1	22.0000n	928.3178	1.1342
3	R2	10.2000K	1.1445K	1.3947
4	C2	22.0000n	928.3178	1.1343

The complete Tweeter section is shown below. All sensitivity values are again less than 1.4, and the circuit's response closely matches the desired target.



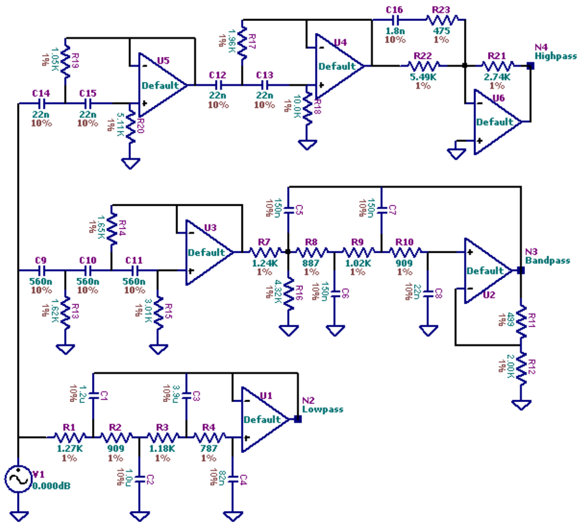


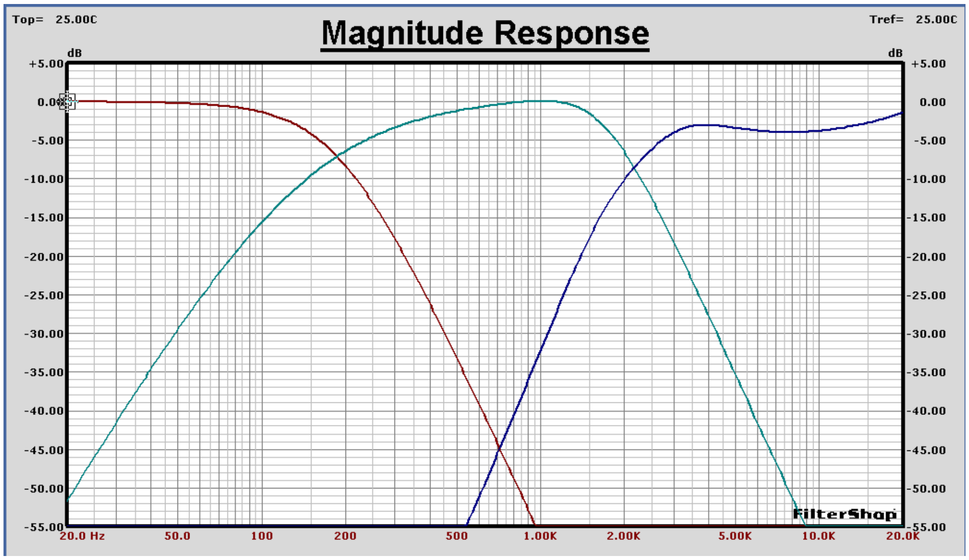
Data Curve: 2: Highpass
Circuit Name: Custom
Components: 12

Index	Comp Name	Comp Value	Frequency (Hz)	Sensitivity
1	R1	1.9600K	569.6072	1.0132
2	C1	22.0000n	928.3178	1.1294
3	R2	10.0000K	1.2272K	1.3893
4	C2	22.0000n	928.3178	1.1295
5	R5	1.0500K	928.3178	1.0087
6	C3	22.0000n	1.7395K	1.1183
7	R6	5.1100K	2.2995K	1.3793

■ Completed System Circuit

We can now combine all of the three sections into the complete crossover system circuit. This is shown below, along with the Magnitude response of all three crossover sections.





■ Crossover Circuit with Acoustic Response

The acoustic transfer functions are now added to the crossover circuit to verify the results. The outputs can now be summed inphase since the Tweeter crossover section reverses the polarity as required. This is shown below.

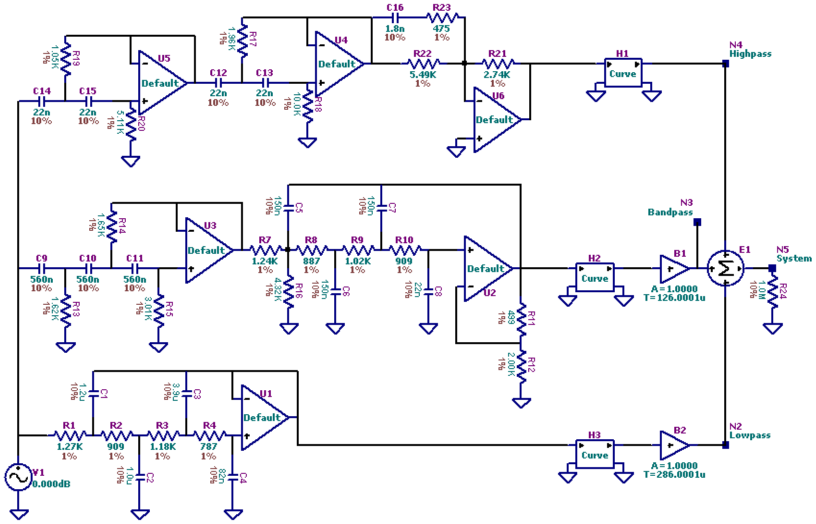
On the following page, the top graph shows the crossover with acoustic response from each section. The lower graph shows the summed system response. The flatness is very near ±1dB with the exception of the transducer ripple at 5kHz. The response is -3dB at 35Hz and 21kHz.

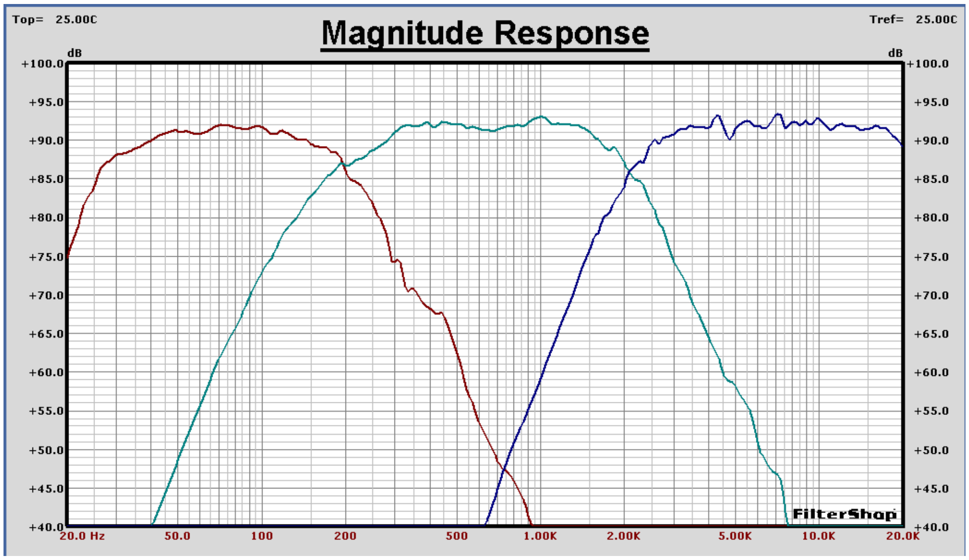
■ Summary

This active crossover design was relatively simple, yet it is extremely stable and provides very high performance. Only six opamp sections were required to optimize the system response for wide bandwidth and very flat response.

The design demonstrates the powerful capabilities of generic transfer function modeling. Any arbitrary transfer function can be combined with analytic transfer functions and quickly analyzed. This technique avoids the problem of time consuming optimization using detailed circuitry.

This completes the Analog Audio Active Crossover Design.

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Magnitude Response
Tref= 25.00C
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+95.0
+90.0
+85.0
+80.0
+75.0
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+65.0
+60.0
+55.0
+50.0
+45.0
+40.0
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200
500
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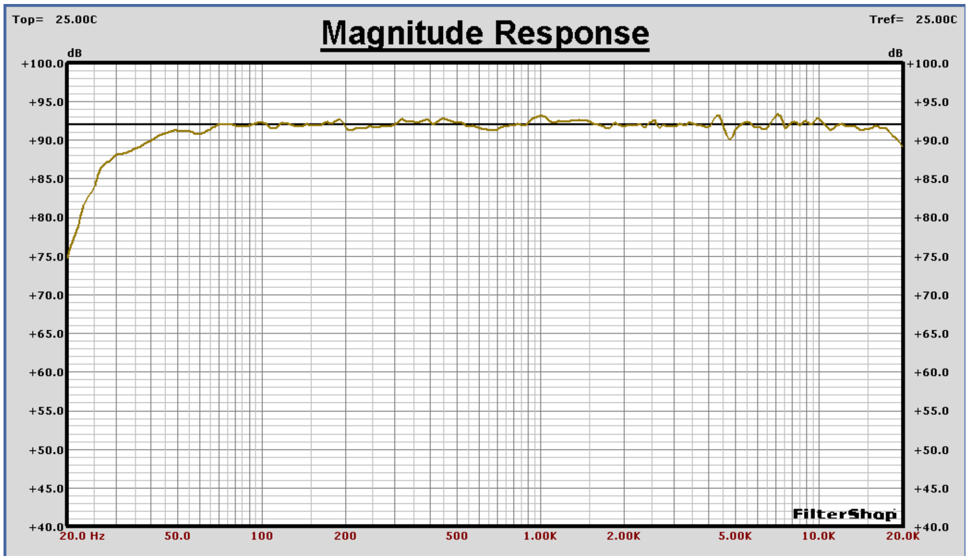
2.00K
5.00K
10.0K
20.0K
FilterShop


Top= 25.00C
Magnitude Response
Tref= 25.00C
dB
+100.0
+95.0
+90.0
+85.0
+80.0
+75.0
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+65.0
+60.0
+55.0
+50.0
+45.0
+40.0
20.0 Hz
50.0
100
200
500
1.00K
2.00K
5.00K
10.0K
20.0K
FilterShop