**π Speakers** P. O. Box 702006 Tulsa, OK 74170 (918) 663-2131

# Speaker motors and passive crossover filters

A study of the performance of loudspeakers in the presence of other reactive components

Linear motor technology is most often used in loudspeaker manufacture, and these devices are reactive in nature. They are usually primarily resistive, but are just as often highly inductive and sometimes primarily inductive. And whether or not a motor has more inductive reactance or resistance, it will always exhibit a mechanical resonant frequency, which causes it to act as though a tuned circuit were in series with the voice coil. Further, the cabinet in which the device is mounted imparts its own reactive characteristics, and all of these form the nature of a speaker motor's reactive load.

Most speakers used for high fidelity purpose split the audio band into more than one region. This requires a series of filters to split the band, and the filter is often one using passive reactive devices connected in line with the speaker circuit. The low impedance nature of the linear motor requires that filter devices also be of relatively low impedance, so interaction between reactive components is quite high. This document is a study into the interrelationship between each of these components, and of the loudspeakers themselves.

Particular attention is paid to high performance two-way loudspeakers. These typically contain very high power woofers in bass reflex or bass horn cabinets, but they cannot generate as much output as their high frequency counterparts. This means that high power compression tweeters must be padded somewhat to match the sensitivities of the subsystems. In systems of this type, tweeters are usually from 10dB to 15dB louder and they also usually begin to rolloff below 20kHz. So the proposed crossover not only splits the frequency band between the woofer and tweeter, but it also acts to match sensitivity of the two subsystems. And since horns create additional resonances, the crossover must damp those as well.

First, we'll examine a few speaker motors using electrical analysis to determine their impedance curves. Then we'll examine proposed crossover networks and filters, and how the parts of the system interact. The software analysis tool, *Spice*, will be used to calculate impedance curves for each part of this study and *Spice* models used will be shown accompanying each graph.

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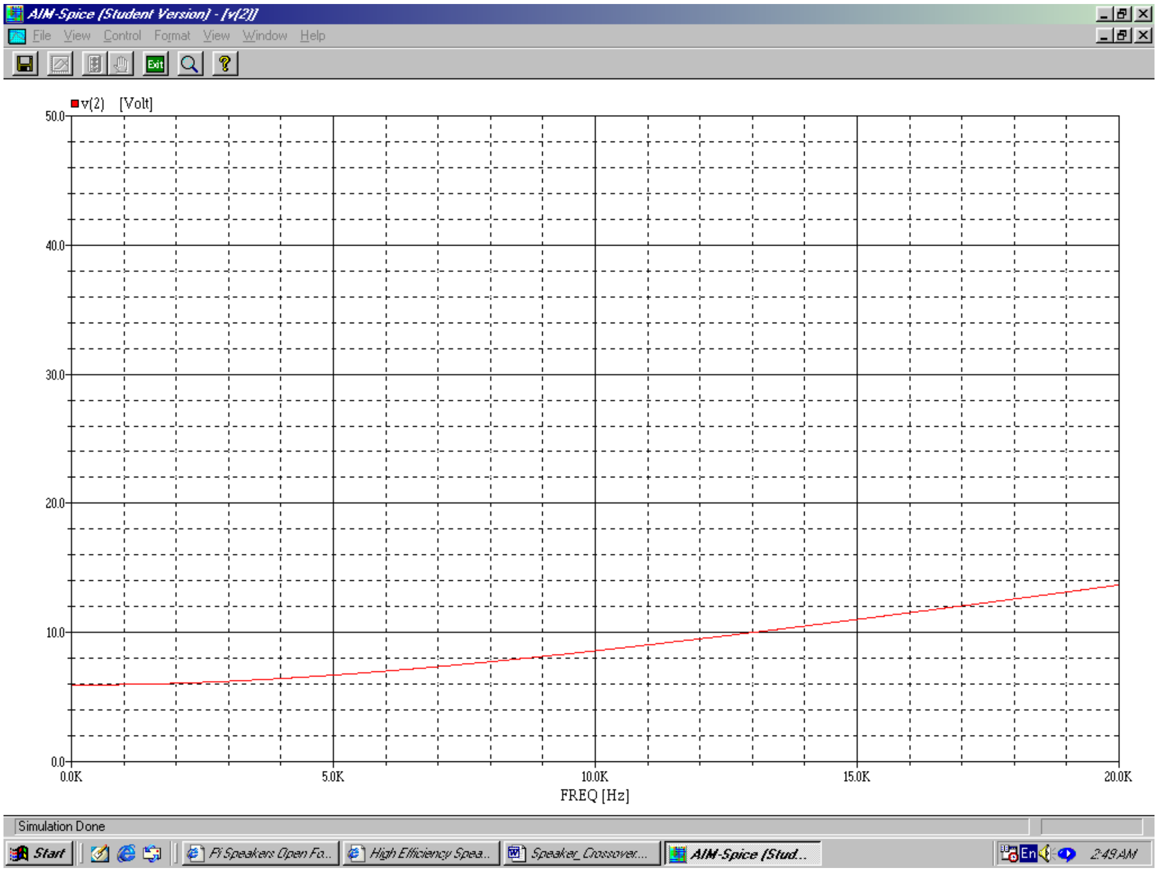
## Idealized speaker motor

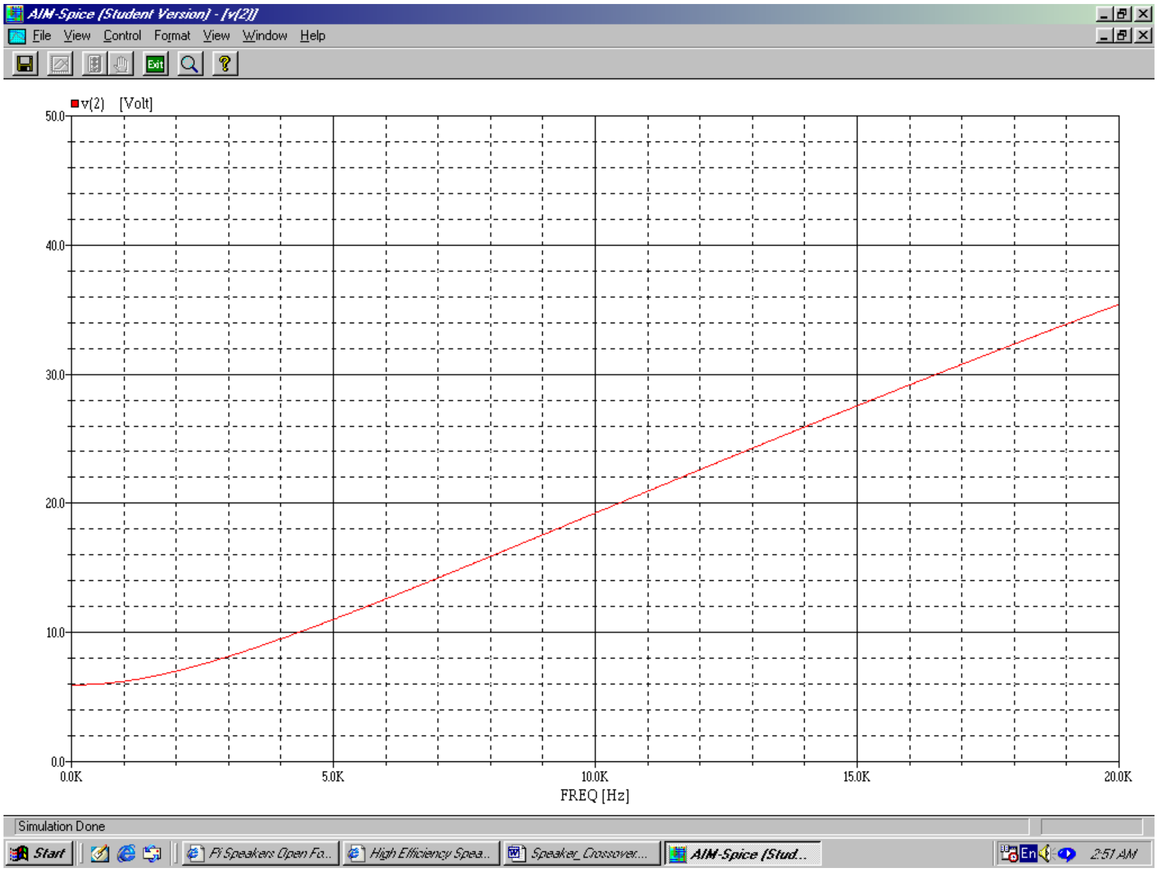
The idealized speaker motor has a fixed resistance value for its impedance, often 8 ohms. Most don't use this simple a value in their models, but another common simplified motor is one having about 75% resistance and about 25% reactive impedance. So an idealized tweeter might be one having 6 Ω resistance and 0.1mH inductance and a woofer might have 6 ohms and 0.3mH to 0.5mH.



Simulation Done

**Idealized Speaker Motor**

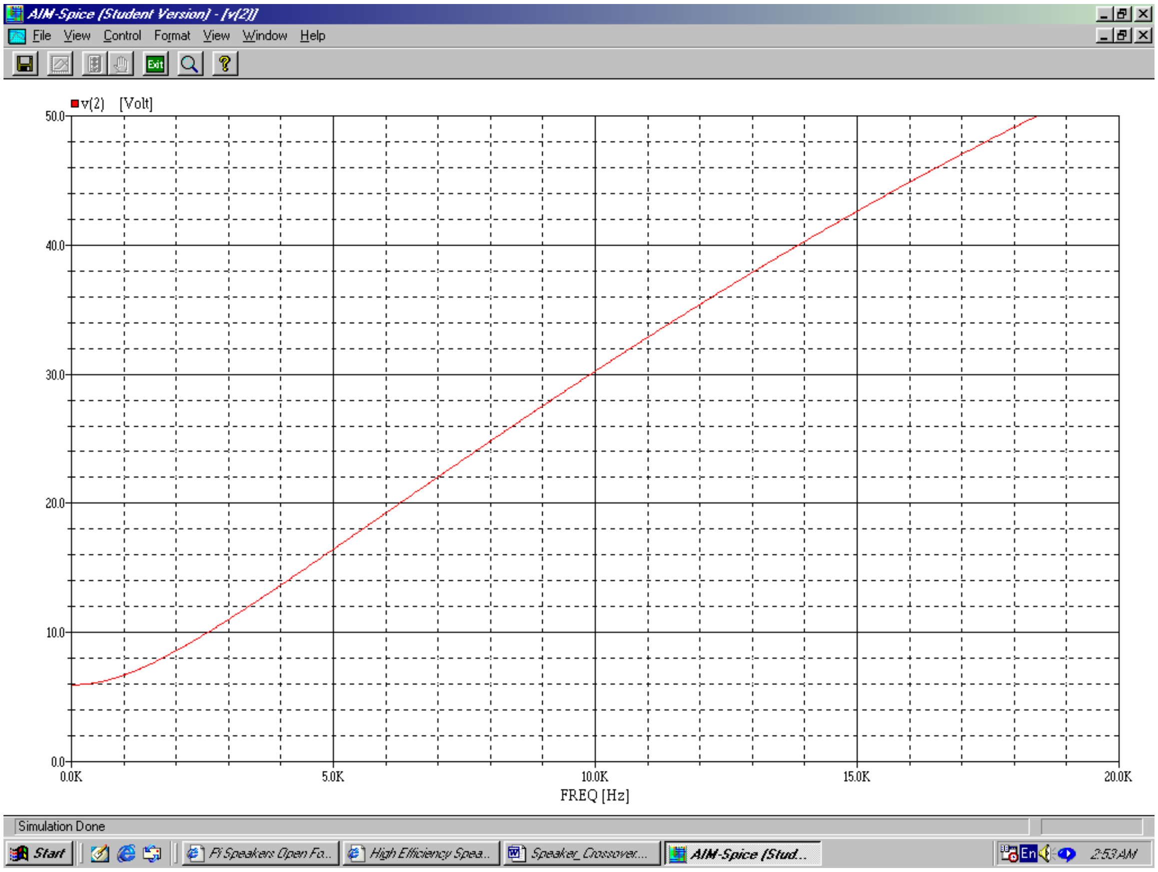
Here is the idealized speaker motor, having 6 Ω resistance and 0.1mH inductance. This is appropriate for some tweeter devices.



Simulation Done

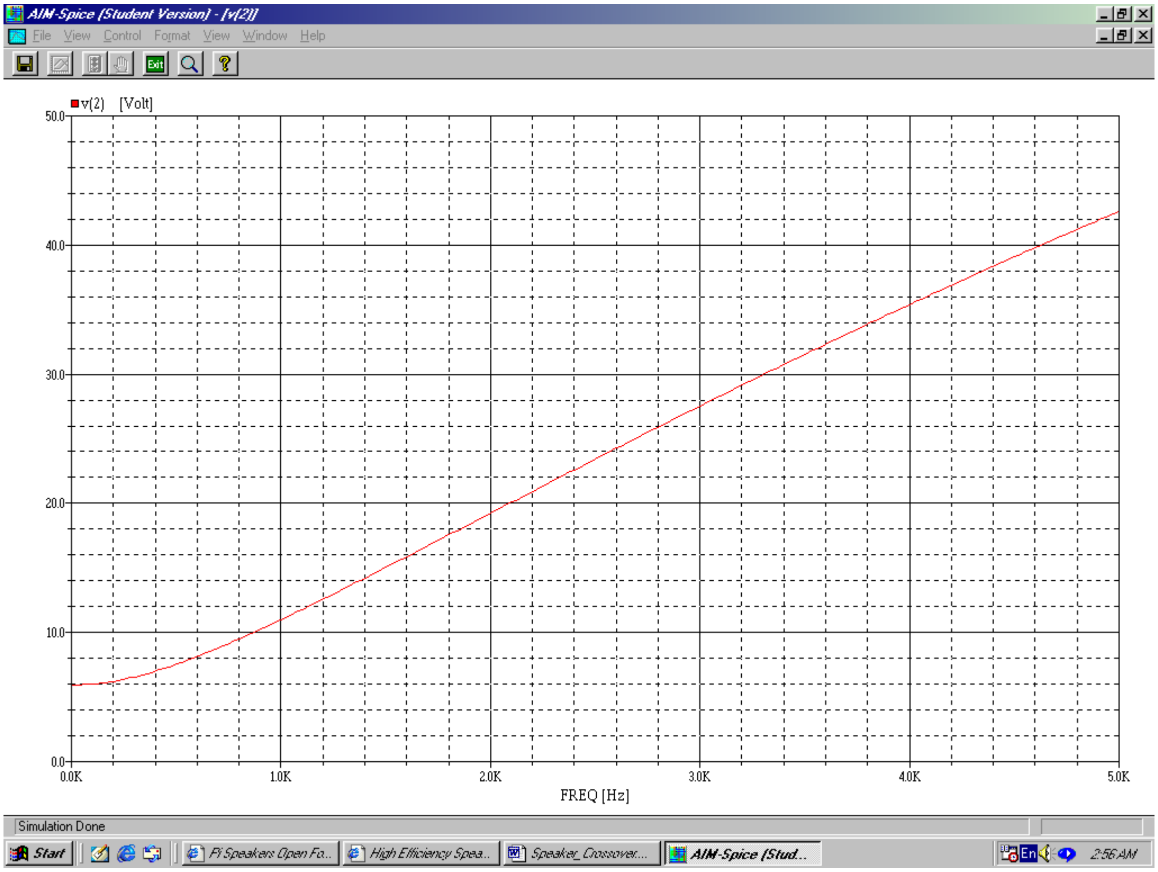
## Idealized midbass or small woofer

This is also a simplified motor, having *Re*=6 and *Le*=0.3mH



**Idealized woofer**

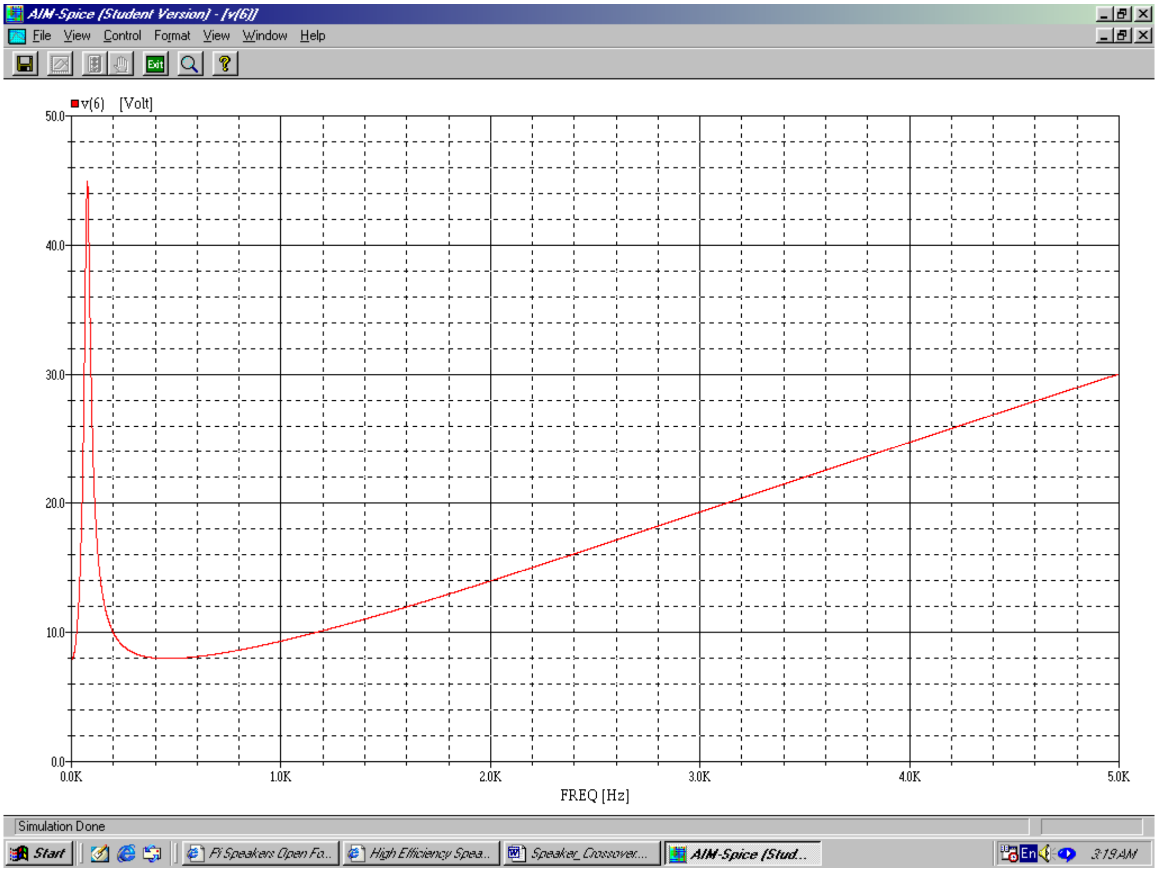
$Re$=6, $Le$=0.5mH



**Idealized high power woofer**

Notice the X-axis has shifted, and 5kHz is now top of scale. This woofer has *Re*=6 Ω and *Le*=1.5mH

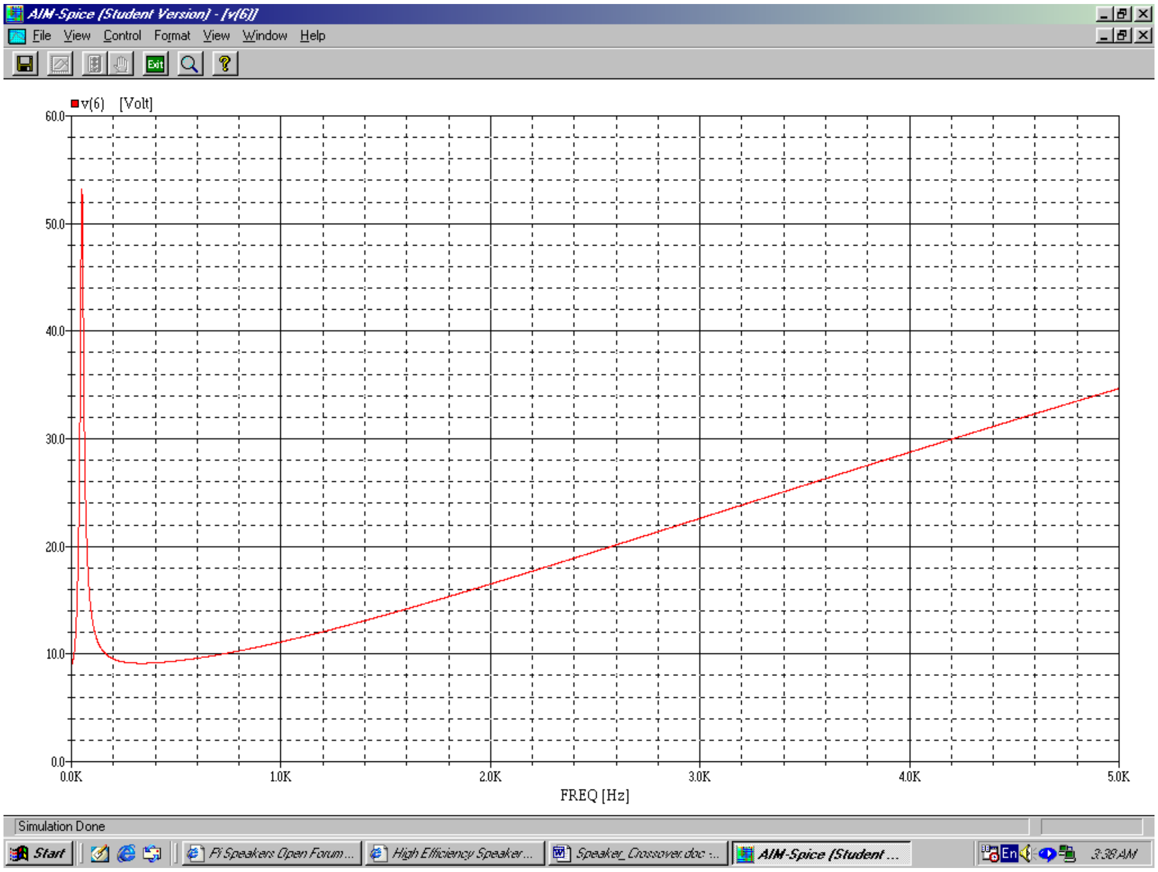
Now let’s look at more realistic devices. Specifically, we will look at the Eminence Alpha 8, Alpha 12, Delta 12LF, Delta 15, JBL 2226, JBL 2426 on a 2370 horn flare, Eminence MD2001 on a Peavey CH-3 and Eminence PSD2002 on the H290 horn flare.



**Eminence Alpha 8**

Spice model:

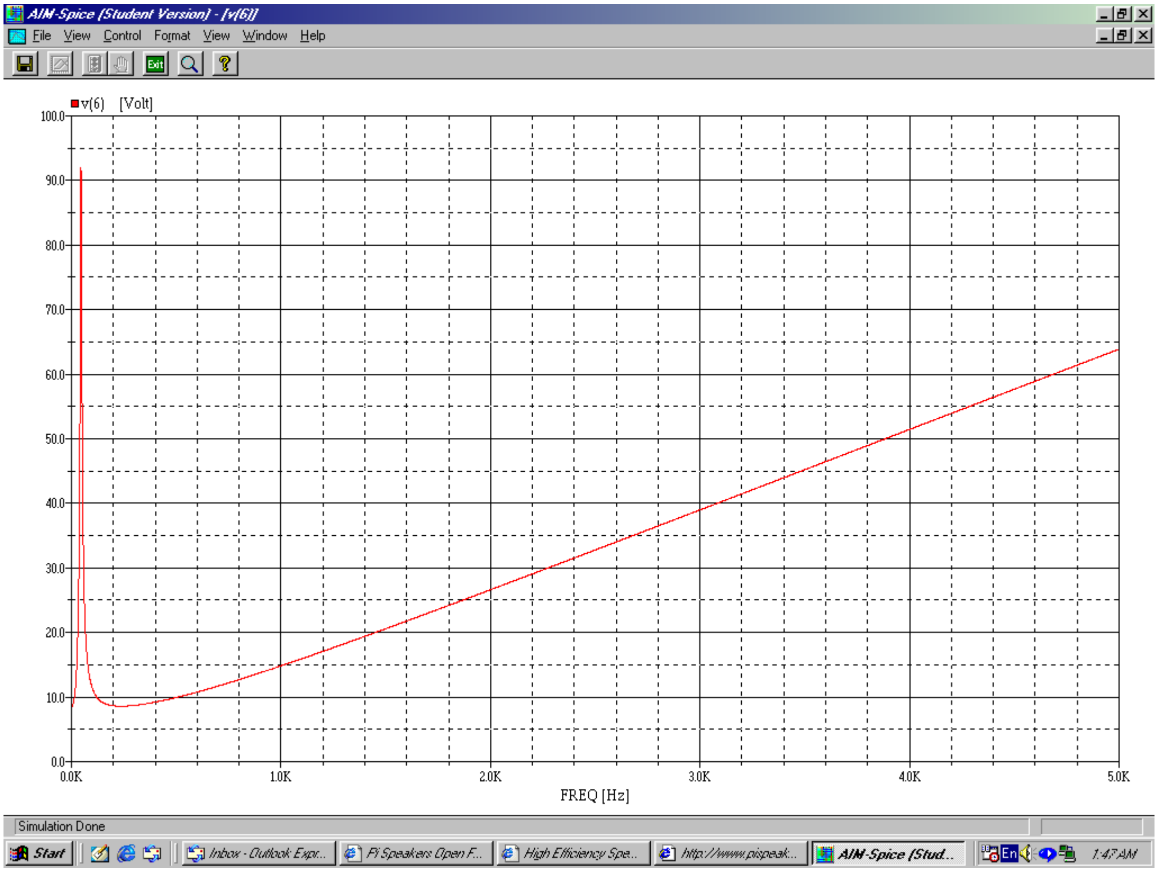
```
! woofer virtual circuit (Eminence Alpha 8)
! voice coil reactance
  R3      6     7     5.27
  L3      7     9     0.65mH
! mechanical reactance (76Hz, Qms=4.5)
 C5       9     0     210uF
 L5       9     0     21mH
 R5       9     0     45
```



## Eminence Alpha 12

Spice model:

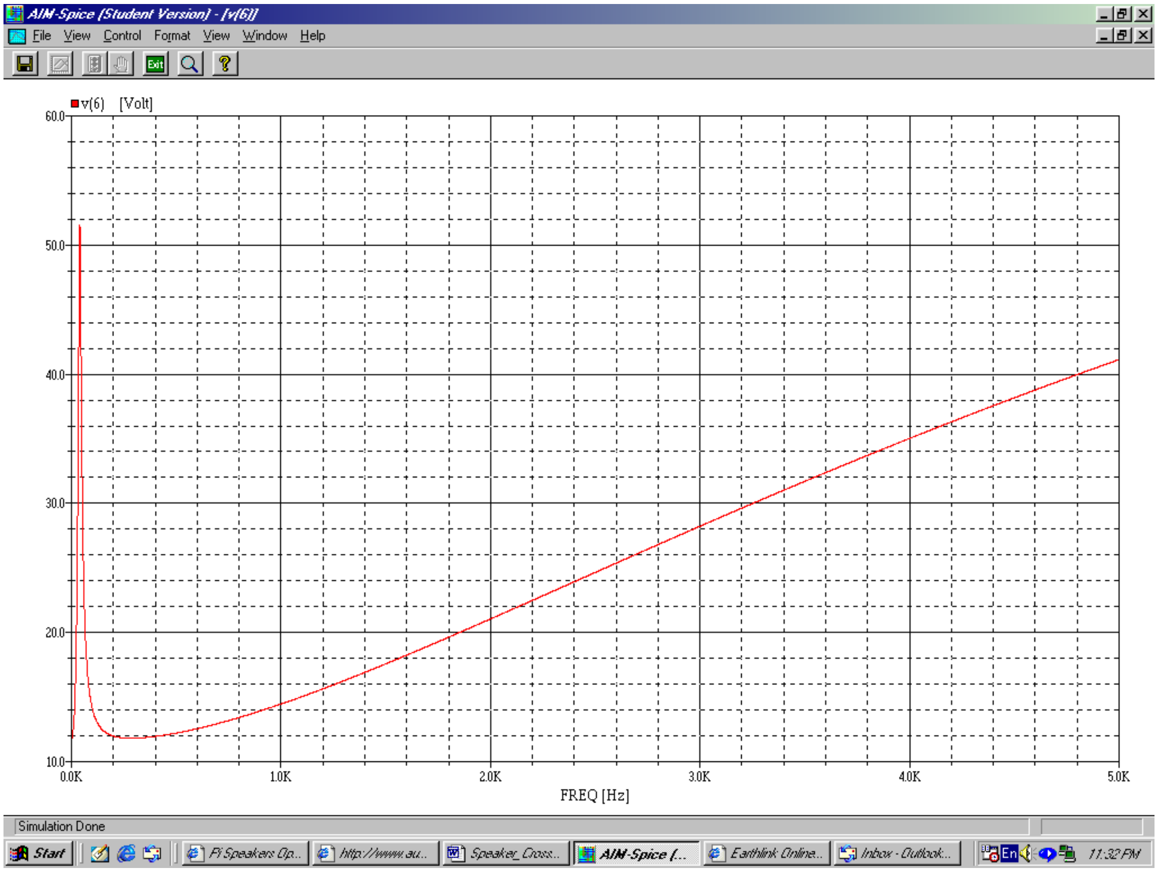
```
! woofer virtual circuit (Eminence Alpha 12)
! voice coil reactance
  R3       6      7      6.30
  L3       7      9      0.79mH
! mechanical reactance (49Hz, Qms=6.53)
 C5        9      0      320uF
 L5        9      0      32mH
 R5        9      0      65.3
```



**Eminence Delta 12LF**

Spice model:

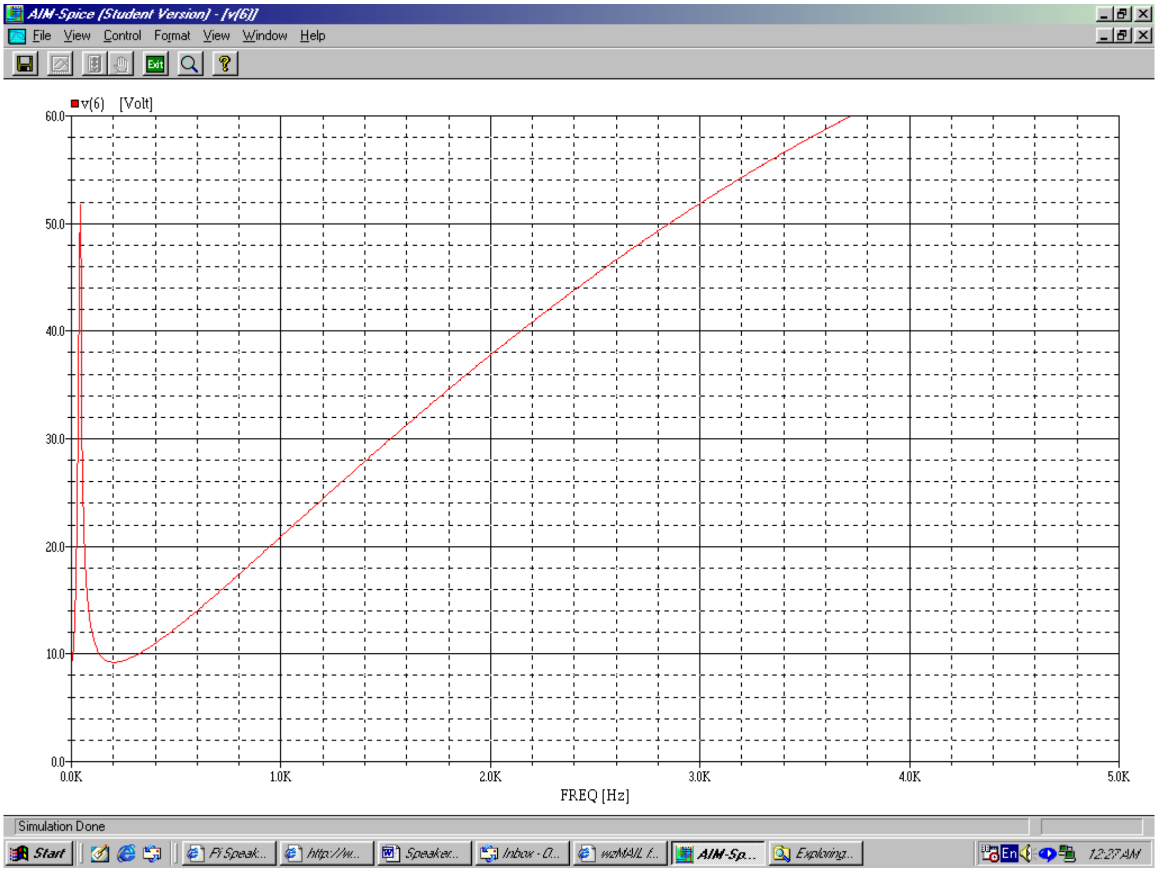
```
! woofer virtual circuit (Eminence Delta 12LF)
! voice coil reactance
  R3      6    7    6.06
  L3      7    9    1.45mH
! mechanical reactance (45Hz, Q=7.28)
 C5       9    0    350uF
 L5       9    0    35mH
 R5       9    0    72.8
```



**Eminence Delta 15**

Spice model:

```
! woofer virtual circuit (Eminence Delta 15)
! voice coil reactance
  R3      6     7     6.9
  L3      7     9     0.86mH
! mechanical reactance (40Hz, Q=6.56)
 C5      9     0     400uF
 L5      9     0     40mH
 R5      9     0     65.6
```

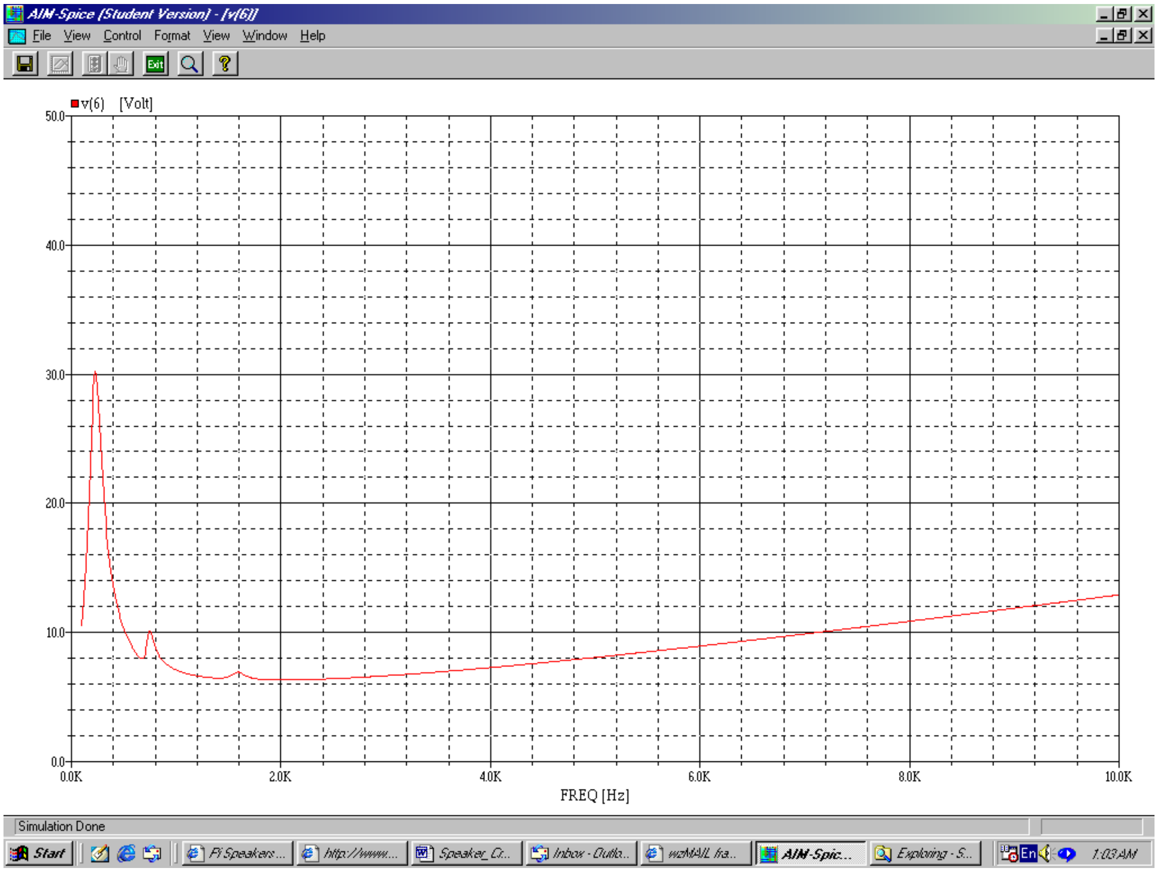


Simulation Done

**JBL 2226**

Spice model:

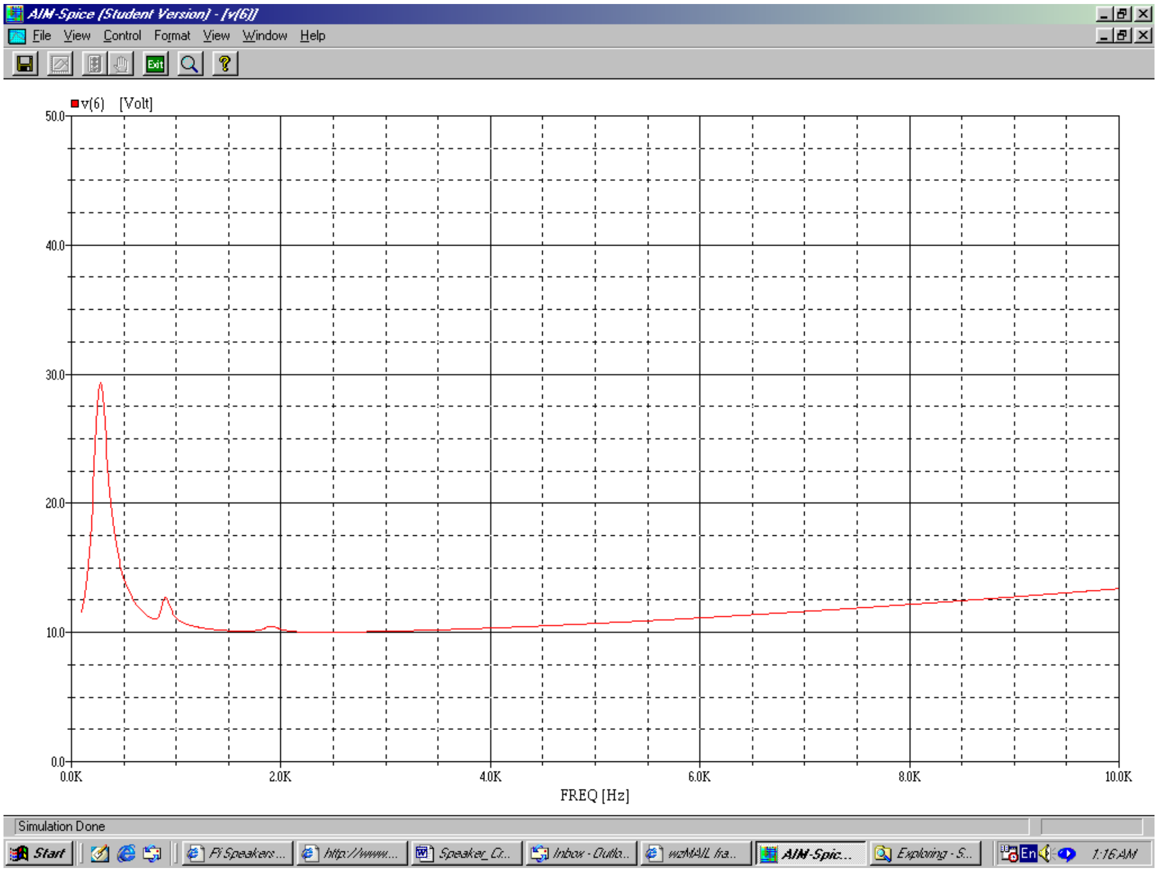
```
! woofer virtual circuit (JBL 2226)
! voice coil reactance
  R3        6       7       5.0
  L3        7       9       1.75mH
! mechanical reactance (40Hz, Q=5.0)
  C5        9       0       400uF
  L5        9       0       40mH
  R5        9       0       50
```



**JBL 2426 on 2370 horn flare**

Spice model:

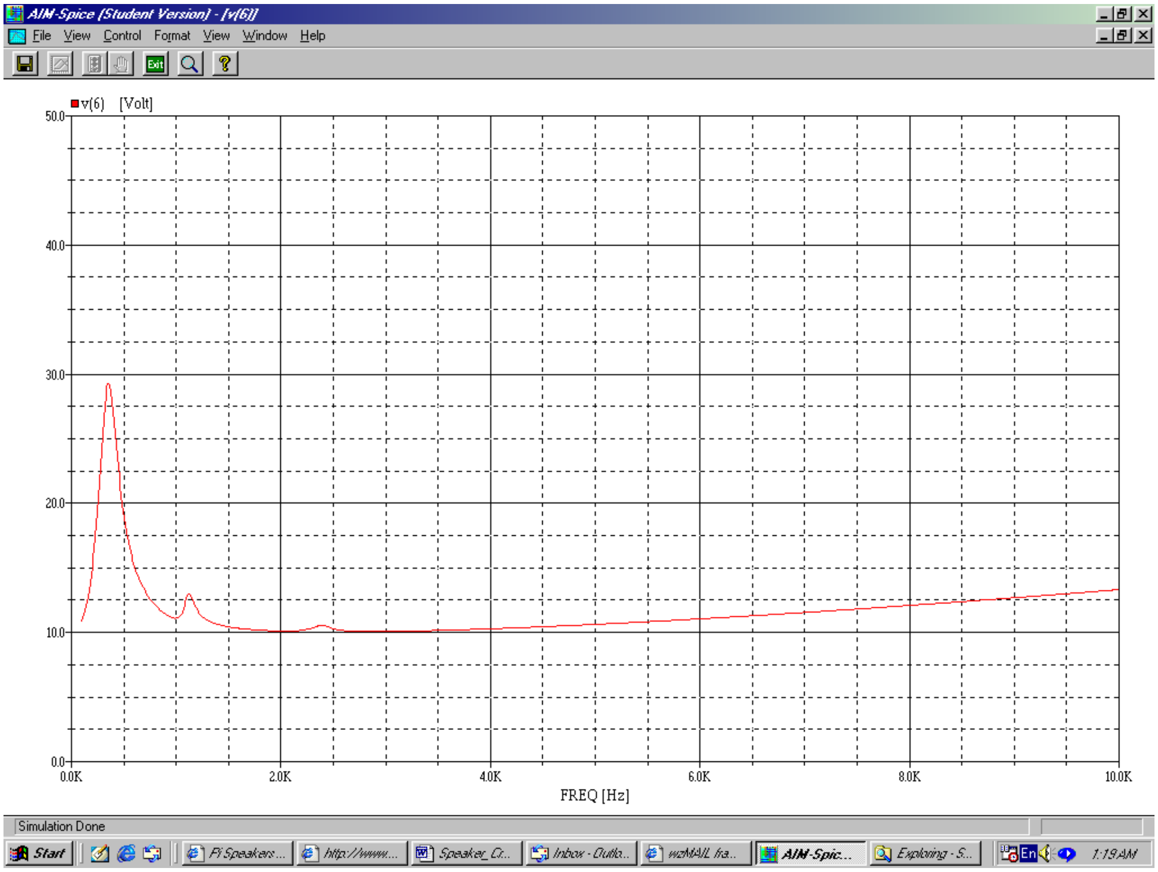
```
! tweeter virtual circuit (JBL 2426)
! voice coil reactance
  R4      6     10    3.3
  L4      10    11    0.1mH
! mechanical reactance (on 2370)
  C6      11    12    30uF
  L6      11    12    3mH
  R6      11    12    100
  C7      12    13    15uF
  L7      12    13    1.5mH
  R7      12    13    100
  C8      13    0     7.5uF
  L8      13    0     0.75mH
  R8      13    0     100
  R9      11    0     20
  C9      11    0     80uF
```



**MD2001 on CH-3 horn flare**

Spice model:

```
! tweeter virtual circuit (Eminence MD2001)
! voice coil reactance
  R4        6       10      6.6
  L4        10      11      0.1mH
! mechanical reactance (on Peavey CH-3)
  C6        11      12      25uF
  L6        11      12      2.5mH
  R6        11      12      100
  C7        12      13      12.5uF
  L7        12      13      1.25mH
  R7        12      13      100
  C8        13      0       6.25uF
  L8        13      0       0.625mH
  R8        13      0       100
  R9        11      0       20
  C9        11      0       66uF
```



**PSD2002 on H290 horn flare**

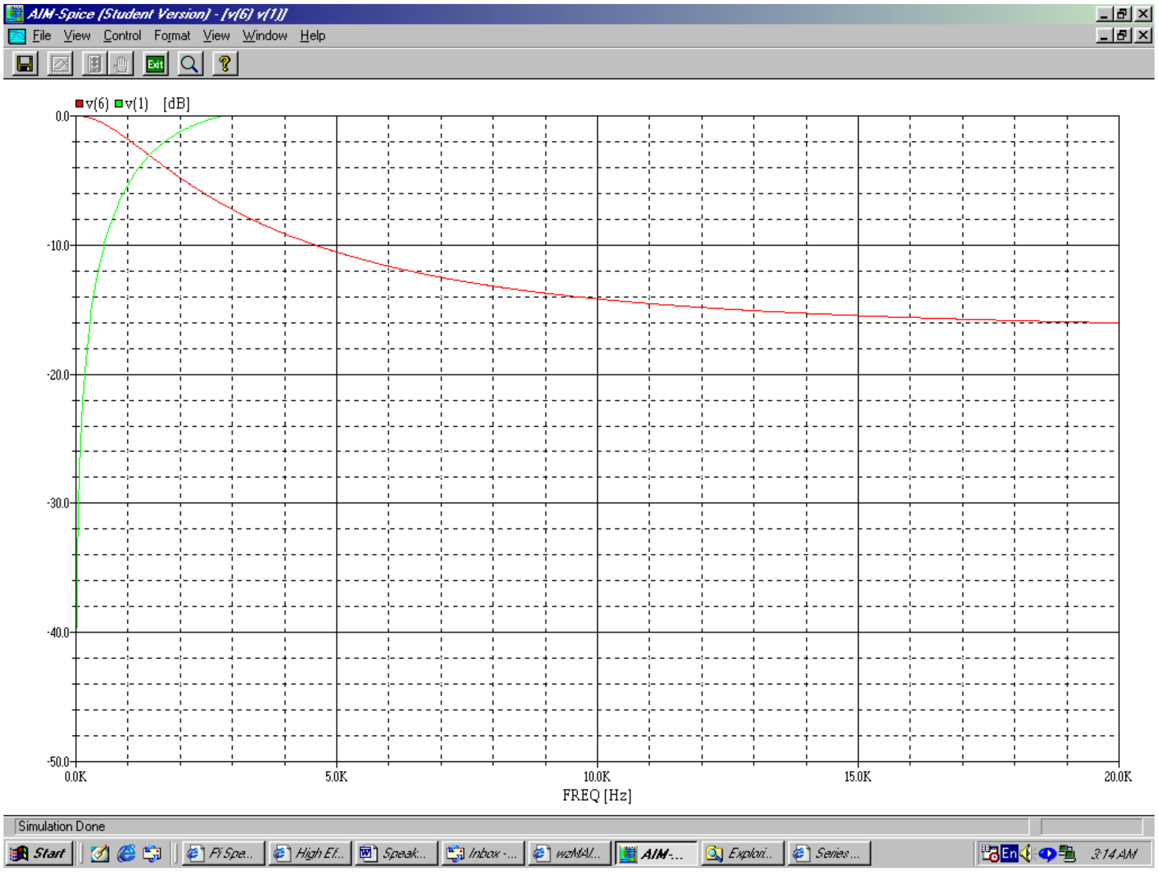
Spice model:

```
! tweeter virtual circuit (Eminence PSD2002)
! voice coil reactance
  R4       6       10      6.6
  L4       10      11      0.1mH
! mechanical reactance (on H290)
  C6       11      12      20uF
  L6       11      12      2mH
  R6       11      12      100
  C7       12      13      10uF
  L7       12      13      1mH
  R7       12      13      100
  C8       13      0       5uF
  L8       13      0       0.5mH
  R8       13      0       100
  R9       11      0       20
  C9       11      0       50uF
```

A few things about these motor impedance curves are immediately evident:

1. The “idealized motor” is purely resistive, but this is not the case in real-world components.
2. Woofers with lower values of voice coil inductance (*Le*) have less increase of impedance at high frequencies than those with higher inductance values.
3. Tweeters on horn flares have relatively small voice coil inductance and their impedance is low at upper frequencies, but they have large impedance peaks at the beginning of their useable range and several subsequent lesser peaks at higher frequencies.

Now, let’s examine some crossover networks, starting with the most simple first order network.



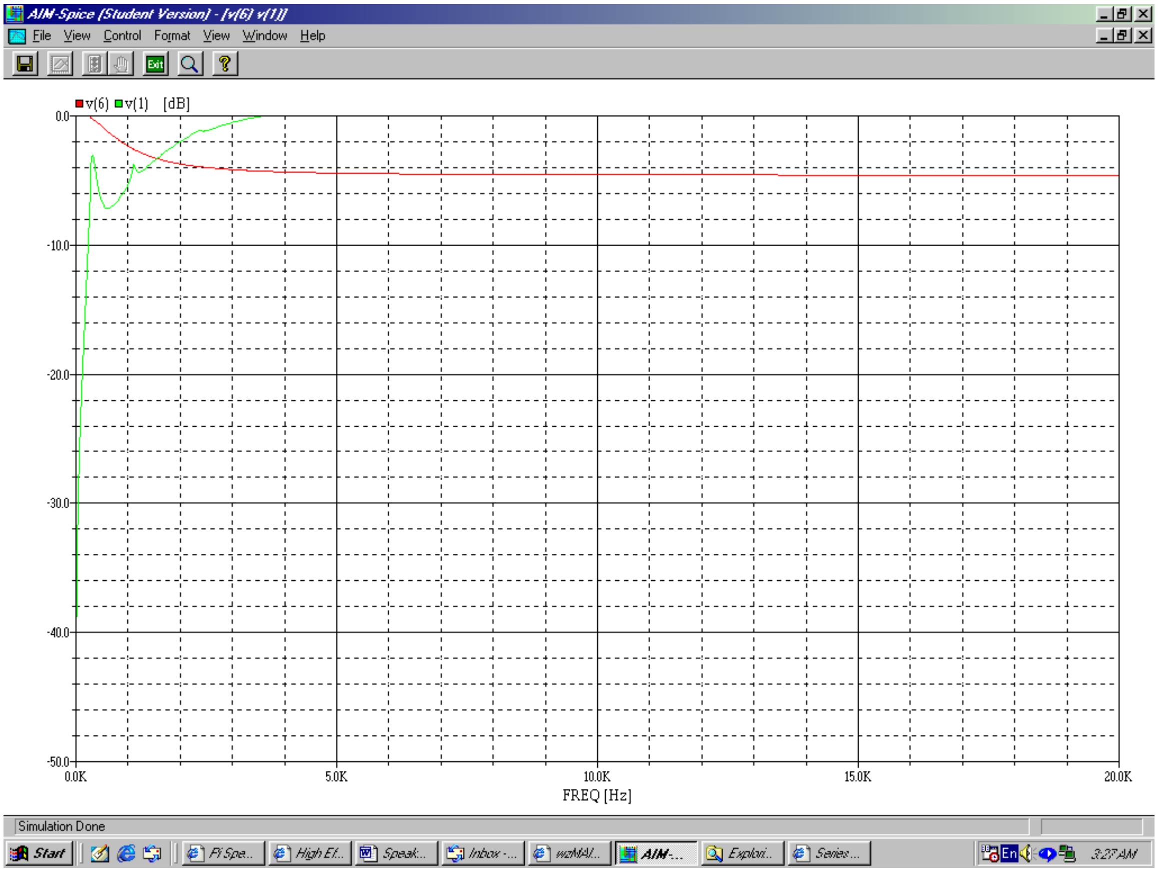
Simulation Done

**1.6kHz first order crossover**

This one is just a 16μF capacitor and a 0.6mH coil. The chart above shows this circuit driving simplified 6 Ω and 0.1mH loads, which are almost purely resistive.

Now let's try this with a couple of real speakers.  Perhaps the Eminence Delta 15 and the PSD2002 on an H290 horn flare.

First, let's examine a traditional first order crossover.

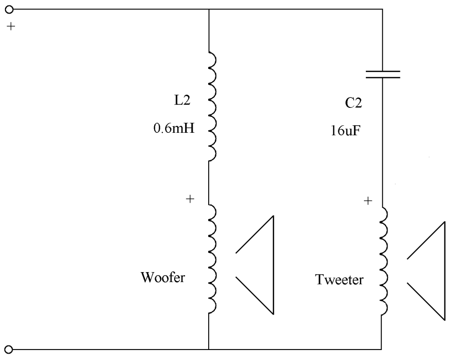


**Delta 15 and PSD2002 using simple first order network**

The model for the first order network and the drivers follows:

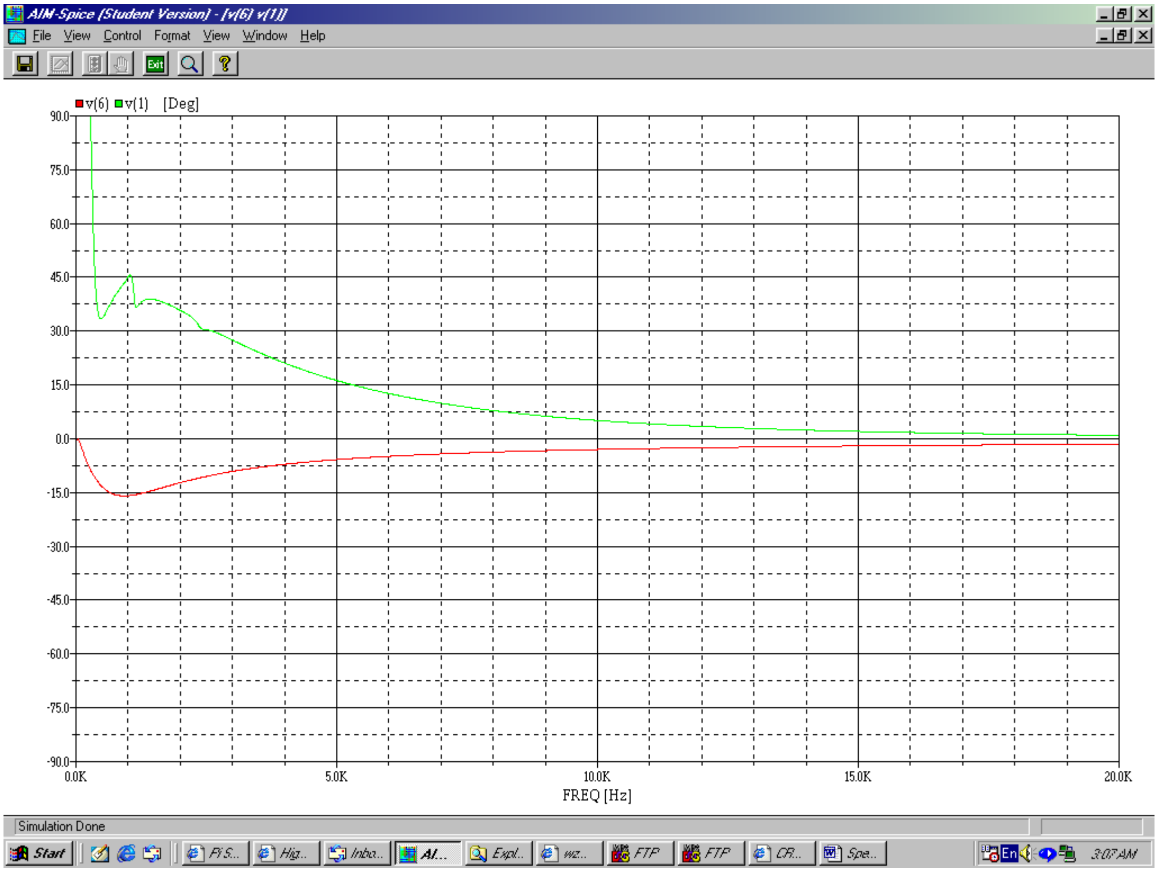
```
! First order network
  L2      5     6     0.6mH
  C2      5     1     16uF
! woofer virtual circuit (Eminence Delta 15)
! voice coil reactance
  R3      6     7     6.9
  L3      7     9     0.86mH
! mechanical reactance (40Hz, Q=6.56)
  C5      9     0     400uF
  L5      9     0     40mH
  R5      9     0     65.6
! tweeter virtual circuit (Eminence PSD2002)
! voice coil reactance
  R4      1     10    6.6
  L4      10    11    0.1mH
! mechanical reactance (on H290)
  C6      11    12    20uF
  L6      11    12    2mH
  R6      11    12    100
  C7      12    13    10uF
  L7      12    13    1mH
  R7      12    13    100
  C8      13    0     5uF
  L8      13    0     0.5mH
  R8      13    0     100
  R9      11    0     20
  C9      11    0     50uF
```

The input to this circuit is across nodes 5 and 0, the woofer output is across nodes 6 and 0 and the tweeter output is across nodes 1 and 0. These points are used throughout this document, and the graphed curves represent the signal at the woofer (node 6) and the tweeter (node 1).



Now let's examine the phase relationship of the drivers in this circuit. Obviously, this is the phase of each driver at its diaphragm, and physical movement in 3D space will generate a *fixed* delay that should be added to the *moving* delay from the phase difference to determine the overall driver interaction at a given location in the listening space.

But here's the phase, as measured at each voice coil:



**Phase response of first order network**

As expected, this is a good phase curve. Through the passband of each device, phase shift is less than 45 degrees. In fact, it can be seen that the woofer's crossover coil has very little effect.

Problem issues to solve with first order crossover filter design:

1. The compression horn has an impedance peak around 1kHz. The peak is caused by horn and diaphragm resonance, and the reactive filter components used in the circuit interact with it.
2. PSD2002 tweeter is 9dB louder than the Delta 15. It must be attenuated and this crossover network has no provision for compensation.
3. The tweeter has significant rolloff in the top octave. Combining this with problem issue number 2, attenuation may be removed in the top octave to extend response in this region.
4. Because of woofer inductance, electronic rolloff never exceeds 4dB. Woofer attenuation is 4dB at 2kHz, but it does not ever rolloff any more than that. Since the Delta 15 woofer generates substantial output well beyond 2kHz, this 4dB attenuation is insufficient.

So let's address these problems one at a time.

The resonant peak of the tweeter is causing an anomaly, and while we cannot correct it fully with a single tank circuit, we can correct at least the fundamental found at the horn's cutoff frequency.

The formulas that describe a tank circuit to provide resonance smoothing are:

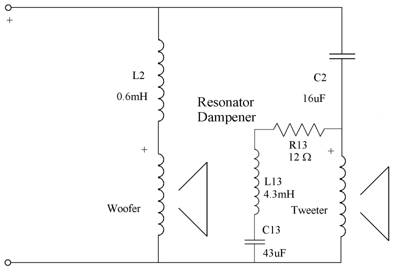
$$Ct = \frac{1}{2\pi F(Qes\,\mathrm{Re})}$$

$$Lt = \frac{Qes\,\mathrm{Re}}{2\pi F}$$

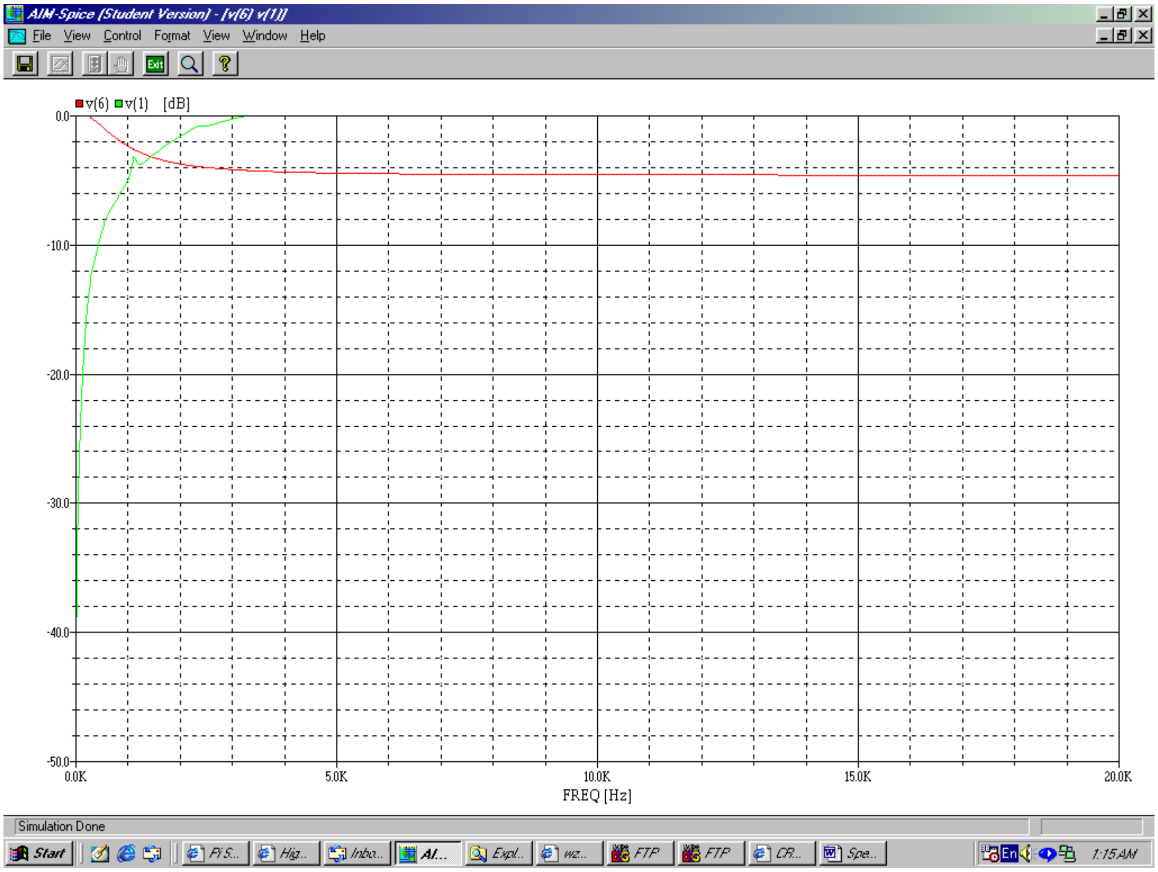
$$\mathrm{Rt} = \mathrm{Re} + \frac{Qes\,\mathrm{Re}}{Qms}$$

Where *Ct*, *Lt* and *Rt* are series reactance values forming a tank circuit placed in parallel with the linear motor. The motor's *Qes*, *Qms* and *Re* values are used to calculate, along with its *Fts* value, which is shown in these formulas simply as "F".

The resonator is added by putting this in the circuit:



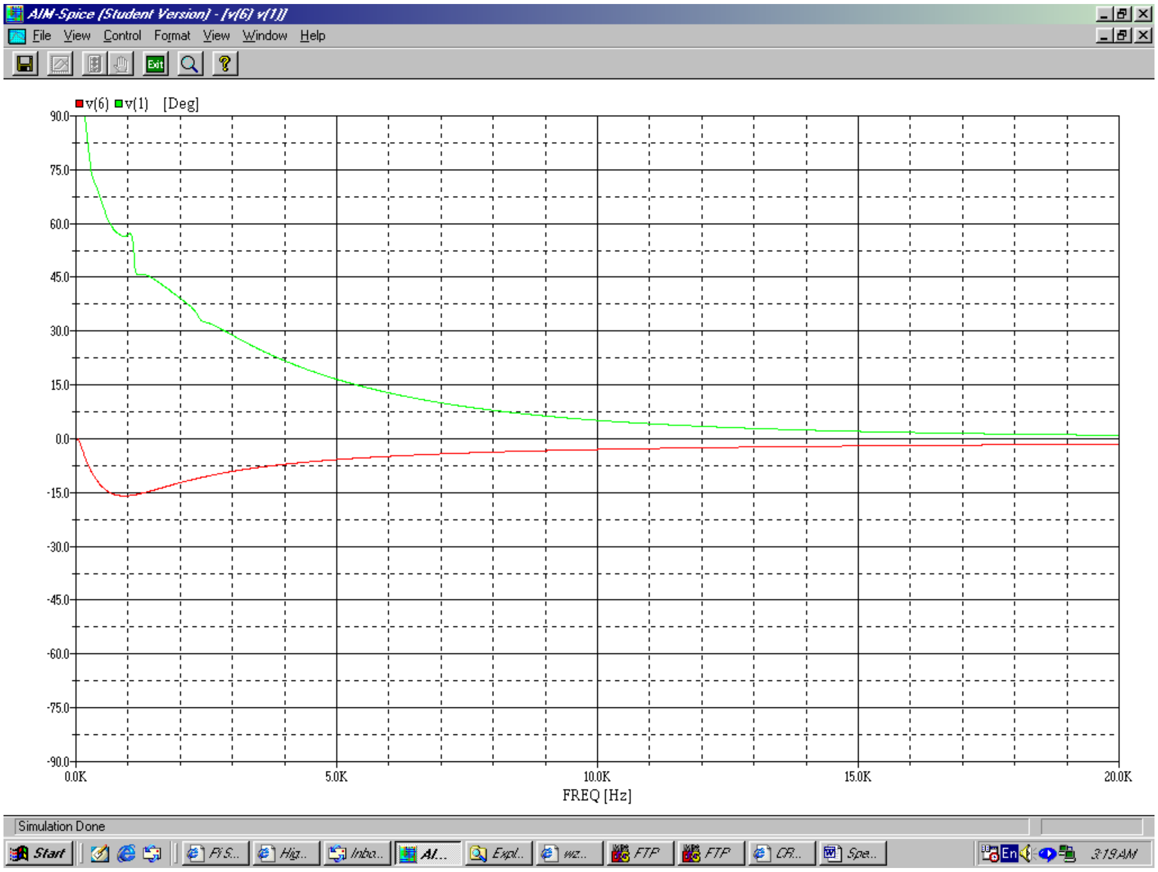
```
! Resonance compensator for tweeter
  C13        1        15       43uF
  L13        15       16       4.3mH
  R13        16       0        12
```



**Delta15 and PSD2002 with first order crossover and electrical resonator**

The resonator, also called a notch filter or “tank” circuit, is formed of three components, *Ct*, *Lt* and *Rt*. These form a conjugate to the first resonance of the horn. The components are connected in series and then the entire network is placed across the driver. In a horn system, there are a multiplicity of impedance peaks. This circuit only acts as conjugate for the first peak, but the others are less in intensity in this case and probably can be ignored.

So let’s examine the phase now that we’ve put this resonator into the system.

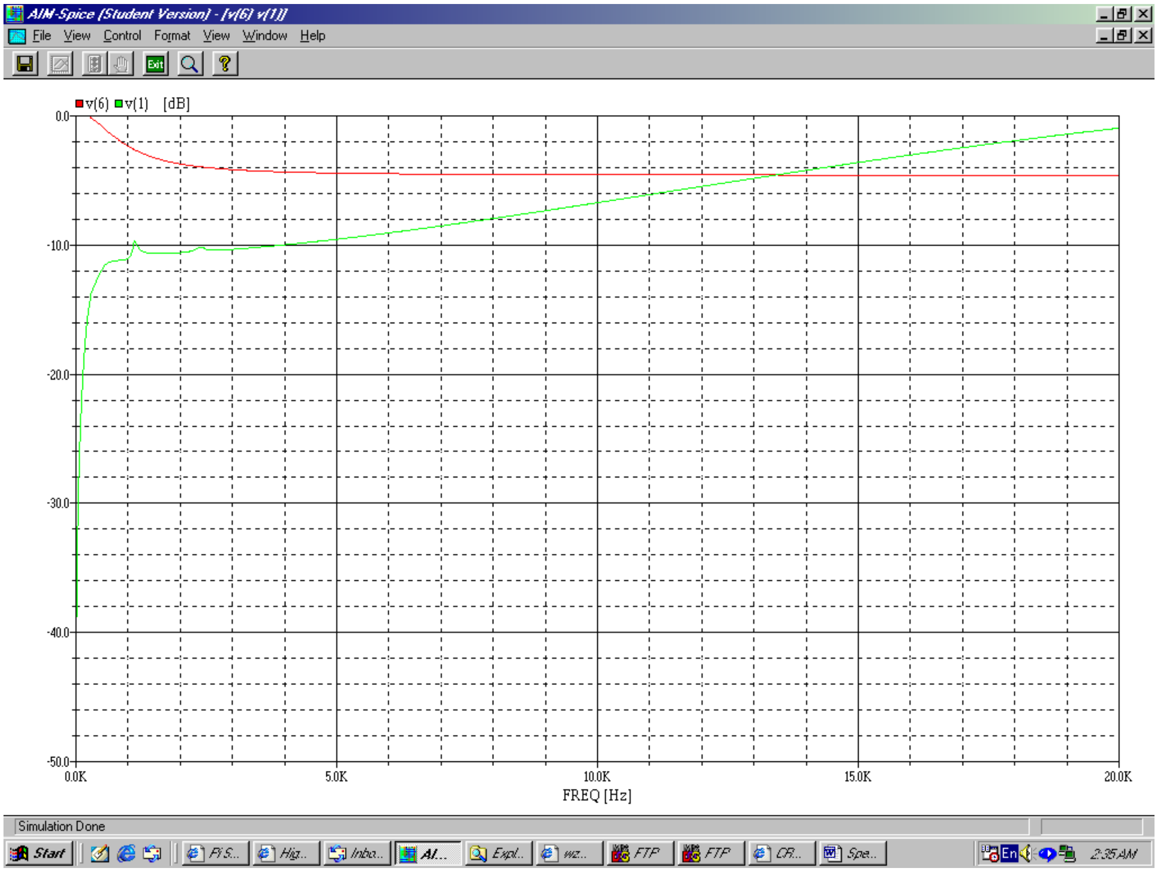


**Phase response of first order network with resonator**

This phase curve is evidence that the tweeter filter is working more effectively. We still see the tweeter being shifted less than 45 degrees in its passband and between 45 degrees and the asymptote of 90 degrees in the stopband. This curve indicates that the filter is working very well.

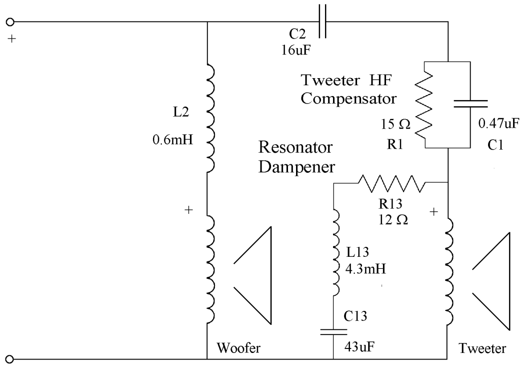
So now let's attenuate the tweeter. First, let's examine our chart of resistor attenuators for 8 Ω loads: We want –10dB attenuation.

| Decibel attenuation | % power | Resistance in ohms |
|---|---|---|
| 0dB | 100% | 0 Ω |
| -2.4dB | 58% | 2.5 Ω |
| -4.2dB | 38% | 5.0 Ω |
| -5.4dB | 27% | 7.5 Ω |
| -7.0dB | 20% | 10 Ω |
| -9.2dB | 12% | 15 Ω |
| -12.3dB | 5.9% | 25 Ω |
| -14.4dB | 3.6% | 34 Ω |
| -15.1dB | 3.1% | 38 Ω |
| -17.2dB | 1.9% | 50 Ω |



**Delta 15 and PSD2002 with first order crossover and compensation network**

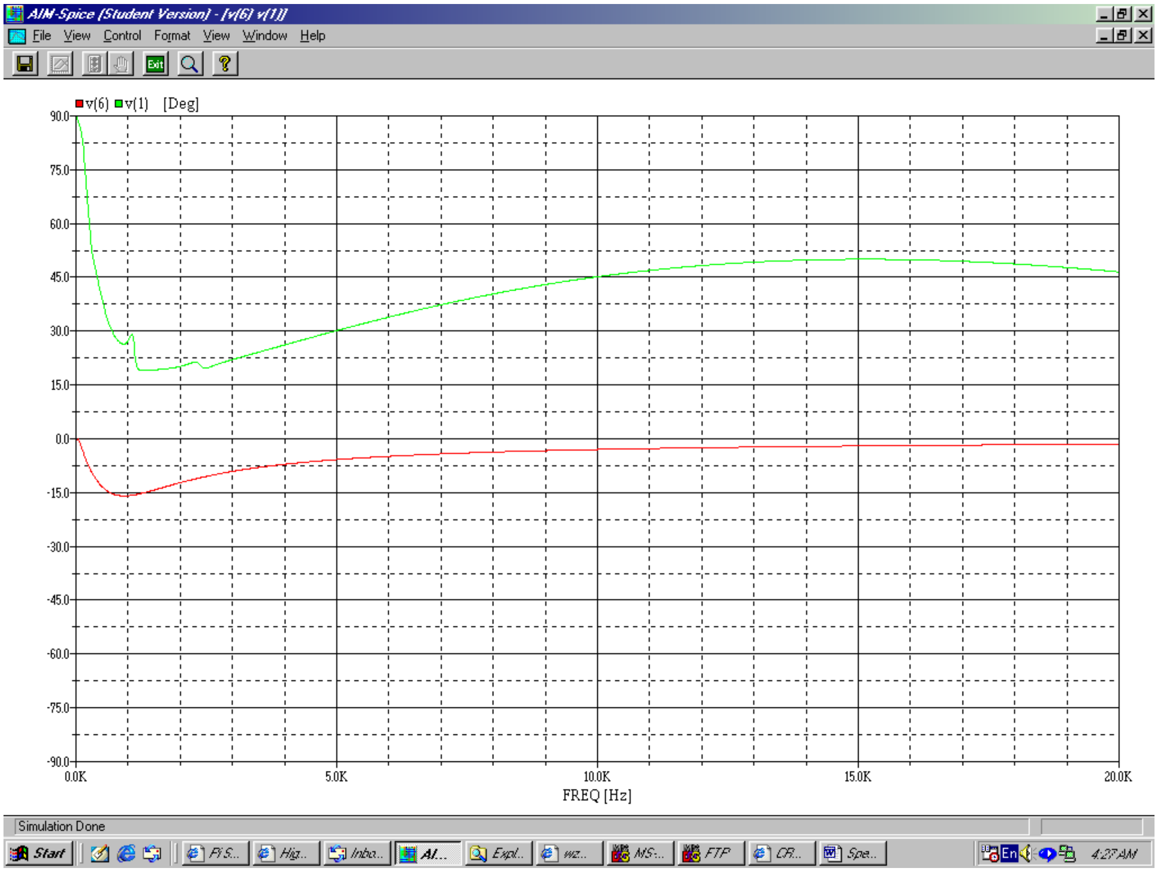
Since we want 10dB attenuation, we chose a 15 Ω resistor for this application. A 0.47μF capacitor is approximately equal to this value at 20kHz, so it will partially bypass the resistor through the top octave. The 0.47μF capacitor is the best choice for a single-part bypass of attenuator values between 30 Ω and 50 Ω, but it becomes more appropriate to choose a larger value when resistance drops below 30 Ω because capacitive reactance is 34 Ω at 10kHz. Still, it performs adequately.



The preceding graph shows the system run with 15 Ω and 0.47μF and the *Spice* representation of this circuit is as follows:

```
! series Compensation components
 R1       3      1      15
 C1       3      1      0.47uF
```

Phase of this circuit:



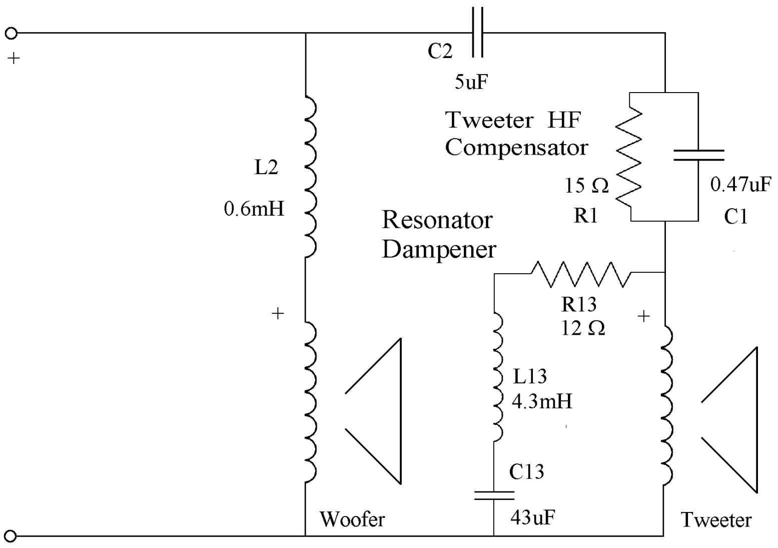
**Phase response of first order network with compensation**

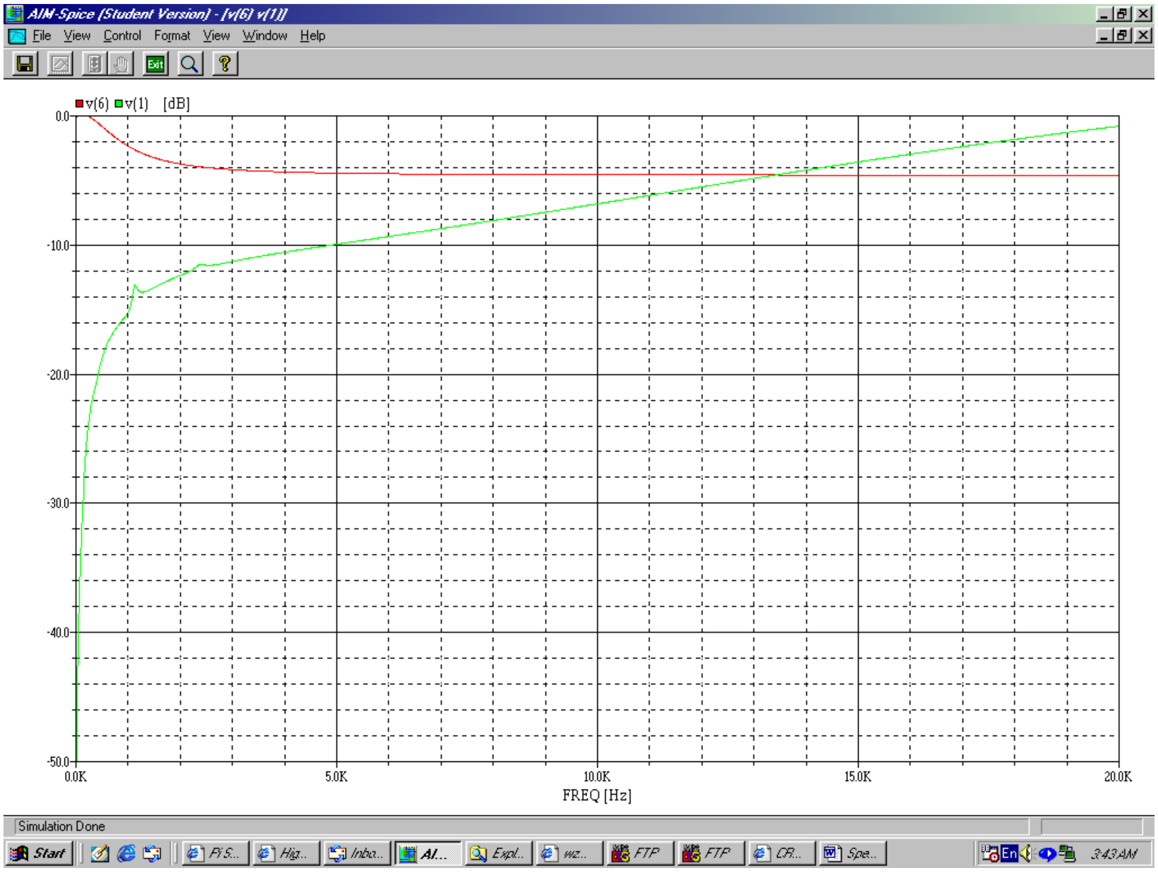
You can see that phase rises to about 45 degrees through the compensated augmentation region – the top octave.

The response and phase curves for the tweeter circuit are good. The peaks at the tweeters lowest octaves aren't troublesome at all; however, the combined actions of the filters have not provided high enough cutoff frequency. The tweeter is receiving almost full power at a relatively low frequency of approximately 500Hz. Since our expected frequency is 1.6kHz, this is over an octave lower than we expected. This combined with the fact that the woofer is unattenuated means that we will have a lot of overlap from 500Hz to woofer cutoff. Loudspeaker output would be quite high and phase interactions, while minimized because of the moderate phase characteristics of low order network, will still be possible for several octaves. The point is that we will have overlap for several octaves.

Part of this may be that we used 6 ohms for our original calculation, which indicated 16µF as an appropriate crossover component. But using 6 Ω instead of 8 Ω does not explain such a shift in expected performance. The biggest reason the crossover point is so much lower than expected is that attenuation resistance has significantly lowered it. Certainly, if we had calculated using too little load impedance, we would crossover higher than expected. But we also would have seen this earlier when we had no compensation installed. The primary reason that our crossover point has shifted is that we have installed this type of compensation network on a first order network without taking consideration of the impedance rise of the load when selecting our crossover capacitor.

This shows us how the compensation circuit reacts in a first order network to lower the crossover point, possibly lower than is safe for the tweeter. The capacitor value was calculated using standard capacitive reactance formula for Xc=6 Ω and F=1600Hz. But with the attenuator resistor, it is more appropriate to calculate using 20 Ω, which is closer to the load the capacitor "sees". This would suggest that a 5µF capacitor be used for crossover rather than the 16µF capacitor originally chosen, and it is much closer to the value predicted using a "load normalized" method.





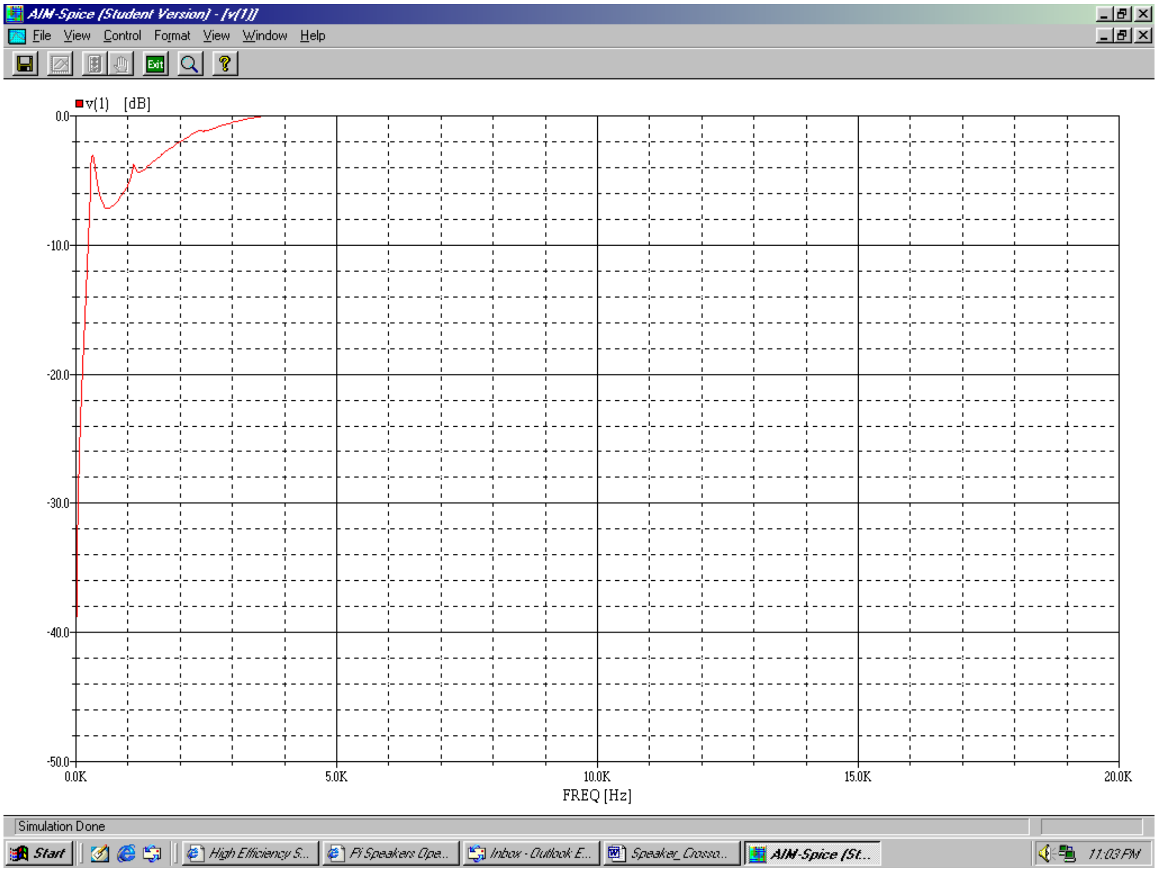
## Delta 15 and PSD2002 with "normalized" first order network and compensation

This is an example using a 5µF crossover capacitor, which is more appropriate for a first order network containing a 15 Ω series attenuator. This particular configuration has lost the benefit of *peaking* offered by the interaction of the larger crossover capacitor and the tweeter, but it does remove signal components below the crossover frequency. Other than that, our entire filter network operates as expected using load normalized Xc = 20 Ω to calculate the appropriate value of crossover capacitance.

***The tweeter circuit is optimal for this particular loudspeaker.***

*To digress for a moment, let's look at the performance of the series compensation circuit when the resonator is removed.* As long as a resonator is employed to damp all unwanted resonant peaks, the series attenuator arrangement is appropriate. But it is important to demonstrate that as series attenuation is raised, the filter grows increasingly underdamped at each resonant mode of the system when no shunt components are installed.

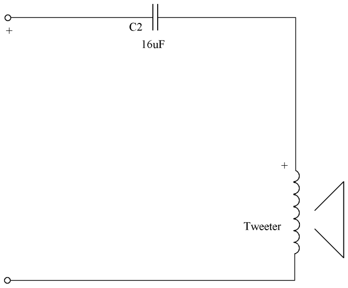
So let’s re-examine the first order network *without* a conjugate resonator for the tweeter.



**PSD2002 using 16µF first order crossover capacitor *only***

This graph shows the signal distributed to a PSD2002, using *only* a 16µF capacitor in series. There are no compensation components in this circuit, whatsoever.

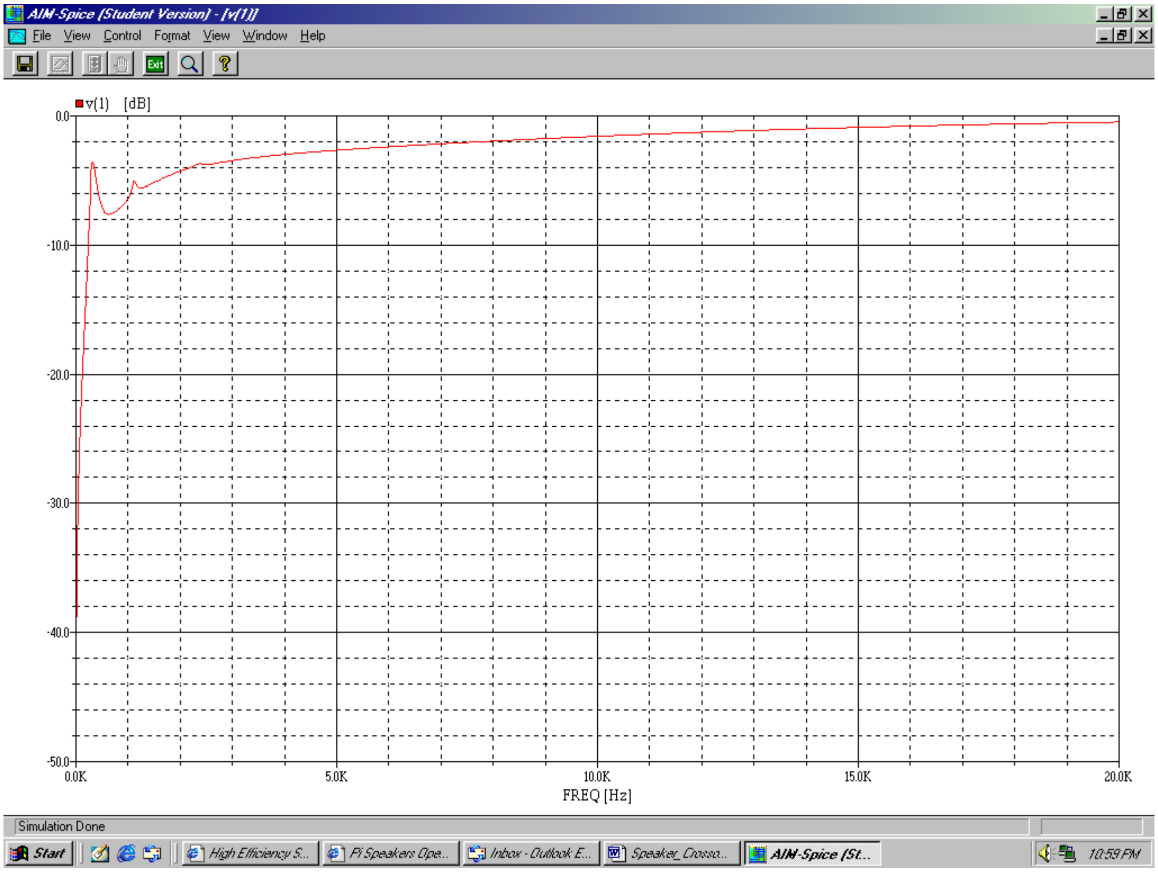
The woofer circuit’s response curve has been removed from this graph.



*Notice in particular that the tweeter has a 4dB peak at about 400Hz, a 1dB peak at 1100Hz and 0.5dB peak at 2200Hz.* At 400Hz, the output of the tweeter should be down –12dB, and you can see from the response curve that it would have been if the tweeter and crossover capacitor weren’t resonating at 400Hz. So because of resonance, there is as much energy at 400Hz as there is at 1.6kHz. *This phenomenon is known as peaking.*

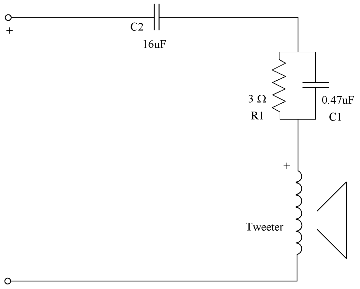
**Something worth noting is that a *single capacitor in series with the tweeter has created this 4dB anomaly.* Users of biamplified tweeters should be cautioned that a protective series capacitor in line will do this. So choose your protective capacitance values with care.**

Now, let’s add a very small attenuator to the tweeter circuit – just as a demonstration. We will add top-octave augmentation using a bypass capacitor so that the compensation circuit retains the same form for comparison. But we will limit attenuation to a very small 3 Ω resistance to attenuate the tweeter circuit only 3dB. We will then raise this amount gradually, so we can see the effects of tweeter/crossover peaking.

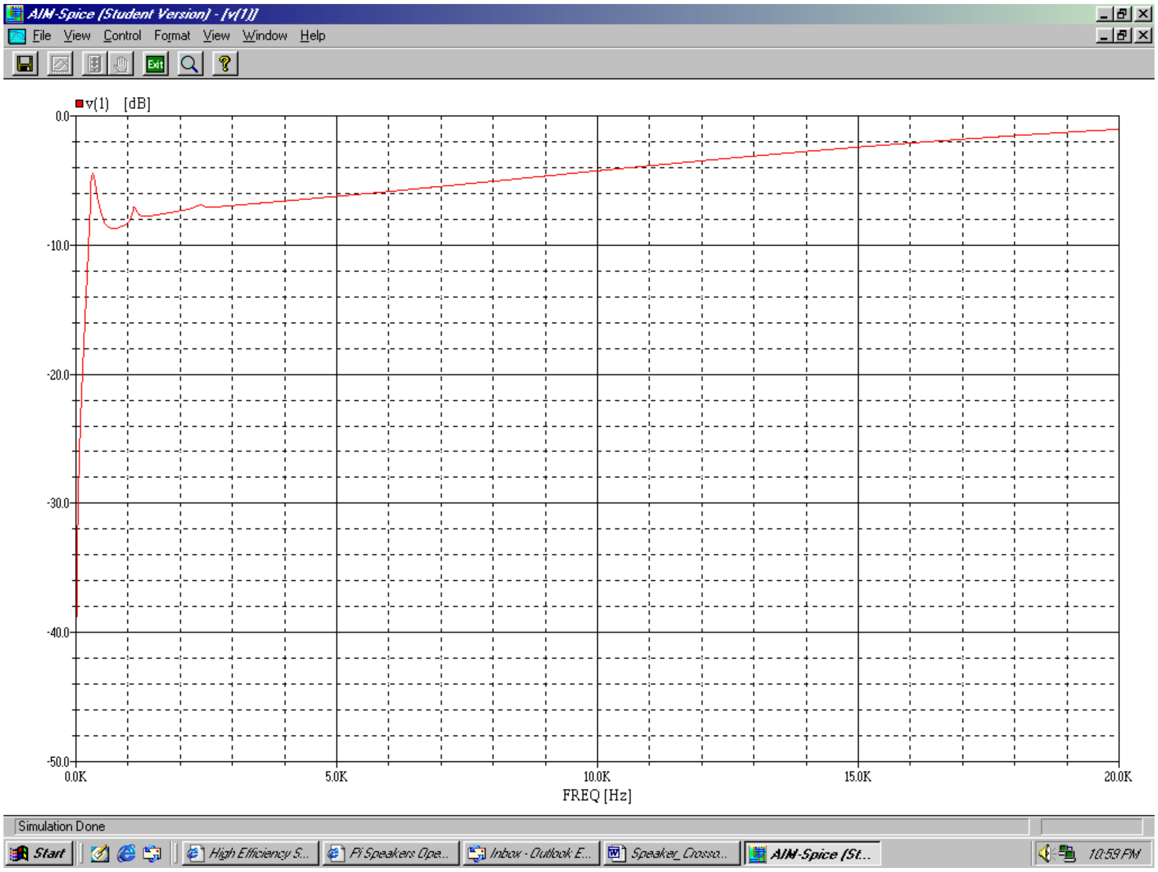


**PSD2002 with first order crossover and 3dB attenuation *without resonator***

Notice that attenuation is approximately 3dB, and the peaks at 400Hz, 1100Hz and 2200Hz are no greater than the uncompensated system. In fact, the tip of the 4dB peak is a little lower than it was in the uncompensated system. But the important feature is performance relative to baseline – which in this case is –3dB. And from this perspective, the peak at 400Hz is only attenuated 1dB. That’s not good, since this frequency is two octaves below cutoff – and our expectation is that 400Hz be attenuated 12dB.



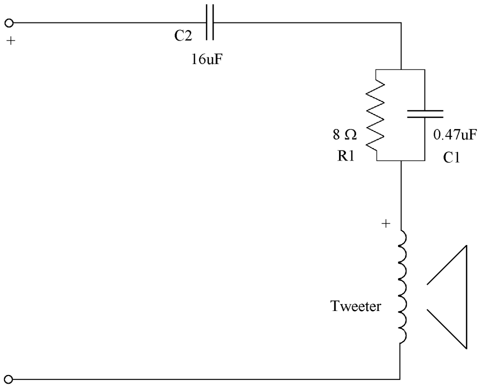
Now, let's examine the system at 6dB attenuation using an 8 Ω resistor.



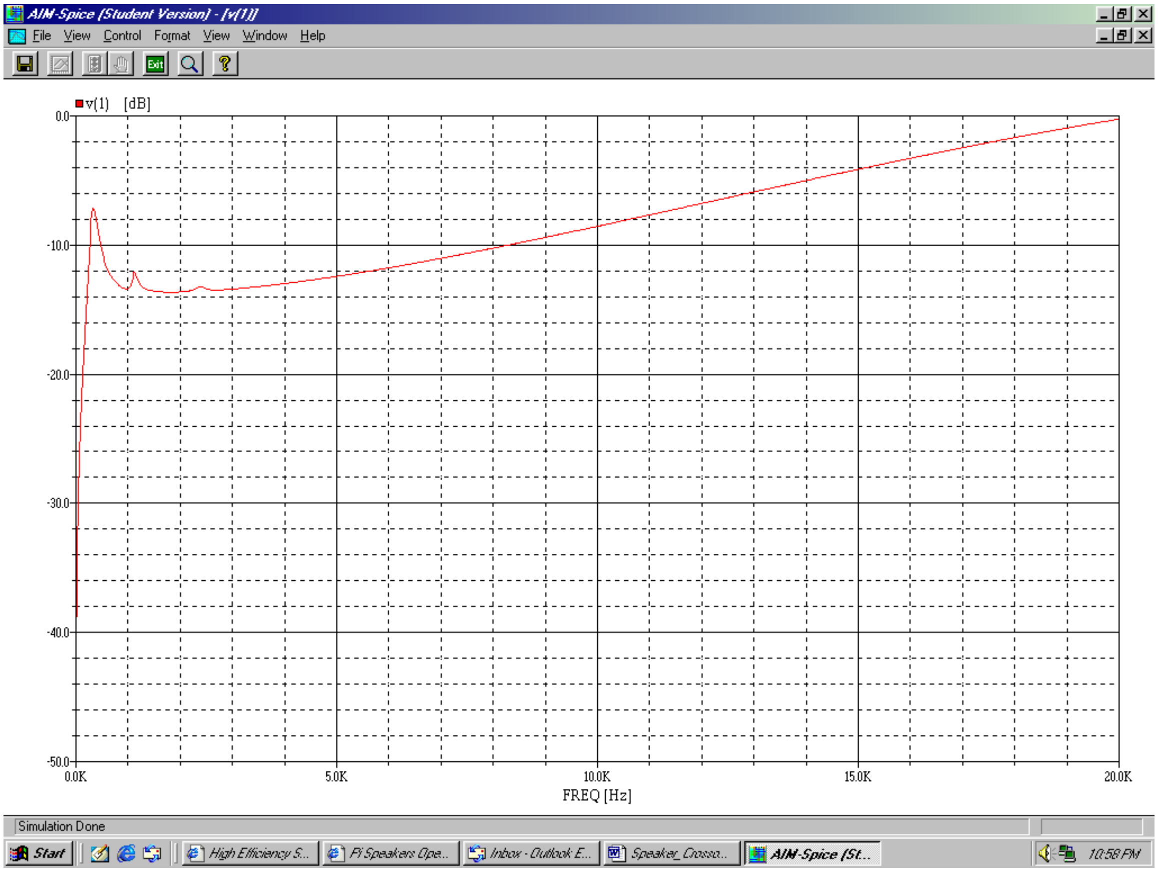
Simulation Done

**PSD2002 with first order crossover and 6dB attenuation *without resonator***

With this circuit, attenuation is approximately 6dB, and the peaks at 400Hz, 1100Hz and 2200Hz are still no greater than the uncompensated system. But these peaks are also not significantly less than the uncompensated even though the baseline has shifted down 6dB. So by comparison with the tweeter's unity reference level, the peak at 400Hz is actually 2dB higher. This isn't a terribly offensive anomaly, and is in fact, difficult to hear. But as you can clearly see, it produces a measurable effect.

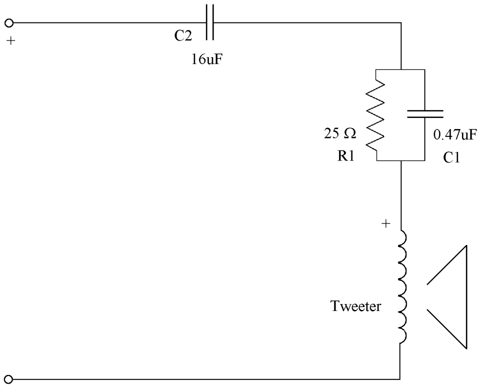


Here’s the system with 12dB attenuation using a 25 Ω resistor.

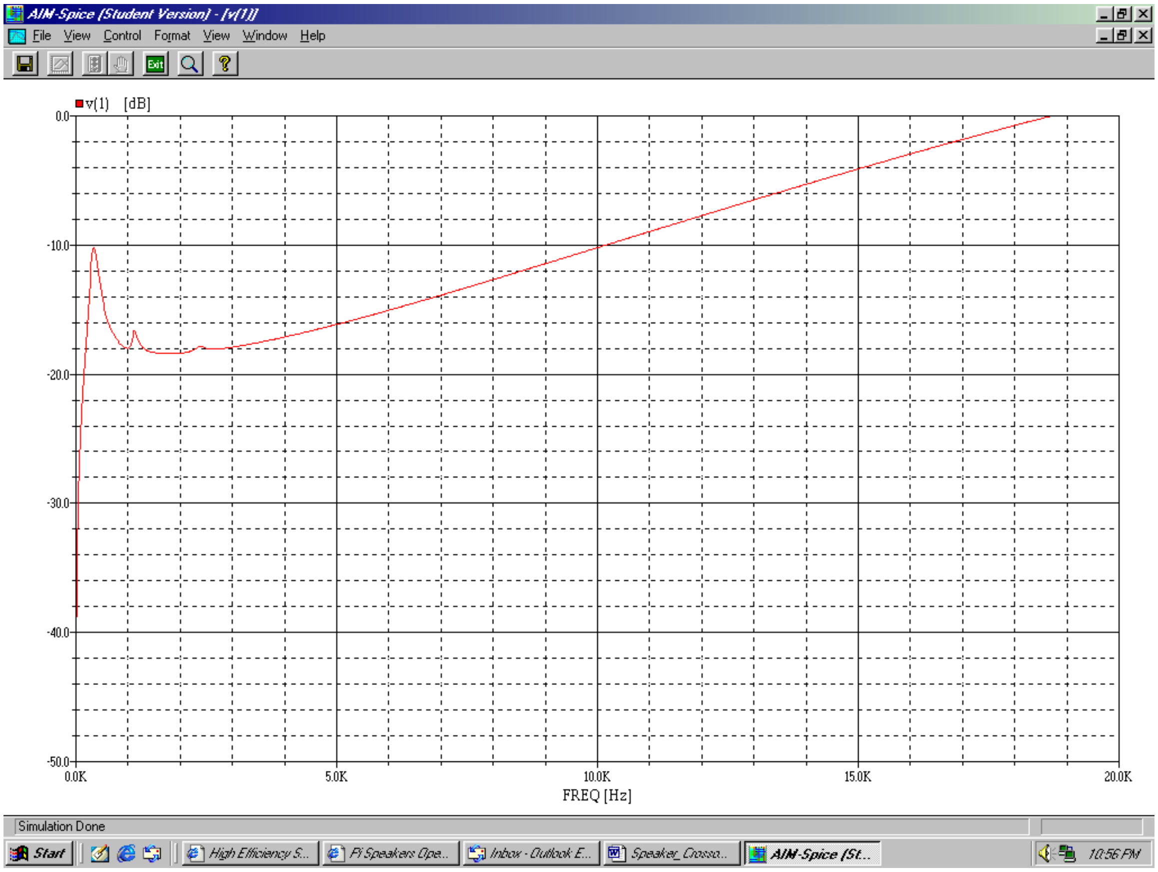


**PSD2002 with first order crossover and 12dB attenuation *without resonator***

Since the unity level is now 98dB, it is disturbing that output in the lower midrange – below expected cutoff - is 103dB. At this point, we begin to notice the tweeter having abnormally high output in the lower midrange. The listener of a system using this network will not really notice the tweeter sounding “louder” than 98dB, but it will begin to sound noticeably different than another system with a tweeter not having this peak.



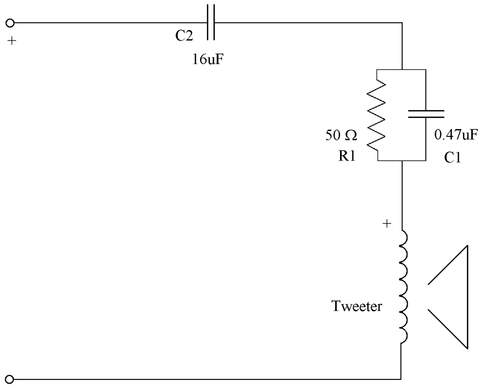
Now, let’s look at the system at 18dB attenuation, using a 50 Ω resistor.



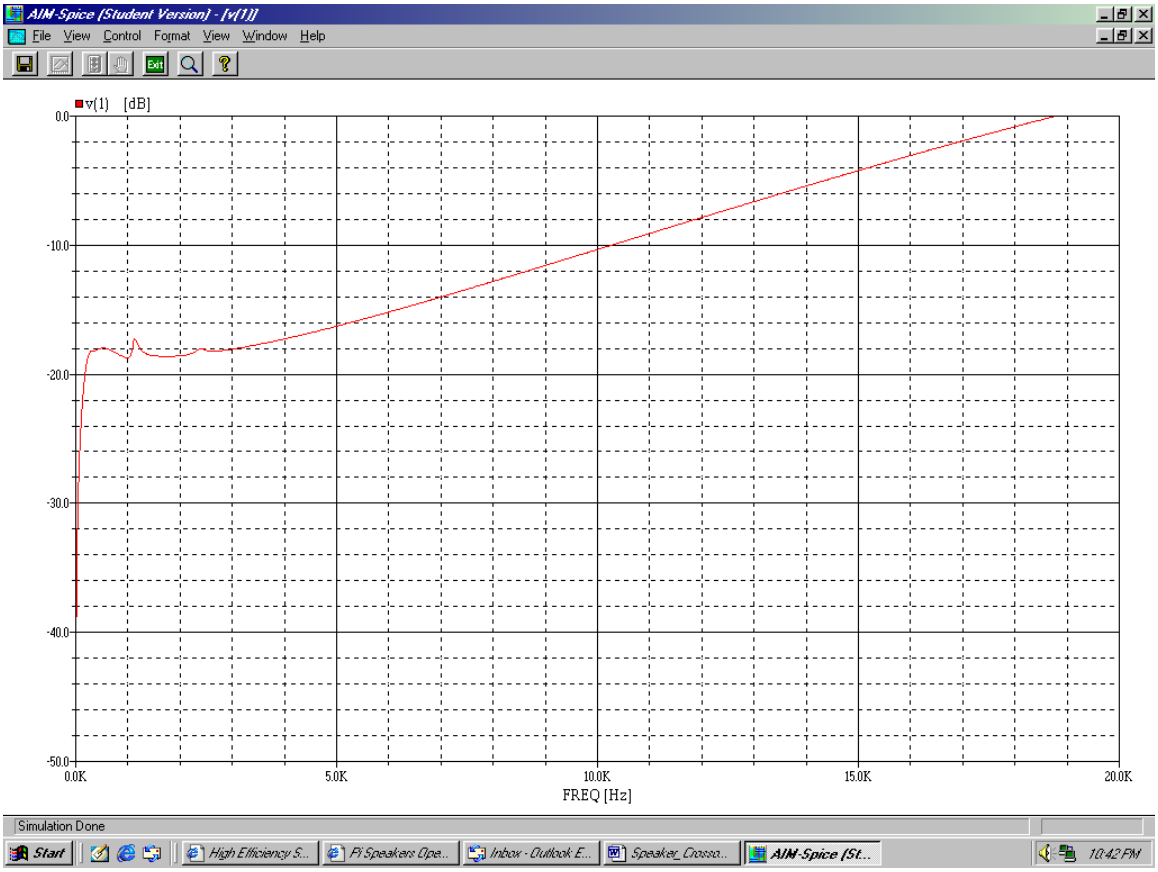
**PSD2002 with first order crossover and 18dB attenuation *without resonator***

At this point, output is unmistakably anomalous. The most pronounced peaking occurs at 400Hz, and is 8dB above the baseline. A tweeter using this filter configuration will sound as though it were attenuated much less than 18dB, since lower midrange is only attenuated 10dB. Also, even if the tweeter was completely incapable of sound output at 400Hz, peaking at 1100Hz raises output nearly 2dB. And for this particular tweeter – the PSD2002 – output at 400Hz is about 90dB@1W/1M, so this 400Hz peak is clearly noticeable.

This particular filter configuration is dangerous for the tweeter because of high power, low frequency content. It also generates a pretty serious anomaly that is easily resolved with the addition of an electronic resonator.



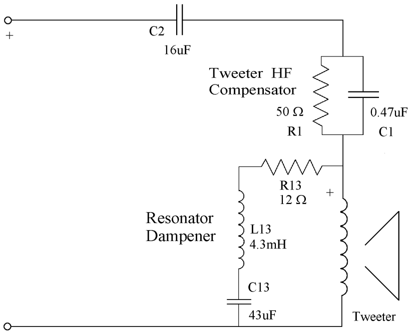
Here is the same network, including the resonator for the tweeter circuit.



**PSD2002 with first order crossover and 18dB attenuation *WITH resonator***

This is an optimally configured series compensation circuit for the PSD2002. The crossover frequency is a bit low, but the filter curve is exactly what we want. Peaking is set very well with this circuit so that response is reasonably flat for several octaves from a few hundred Hertz to 4kHz, where it begins to rise at approximately 6dB/octave. And the crossover frequency can be set higher quite easily, by choosing a different value crossover capacitor.

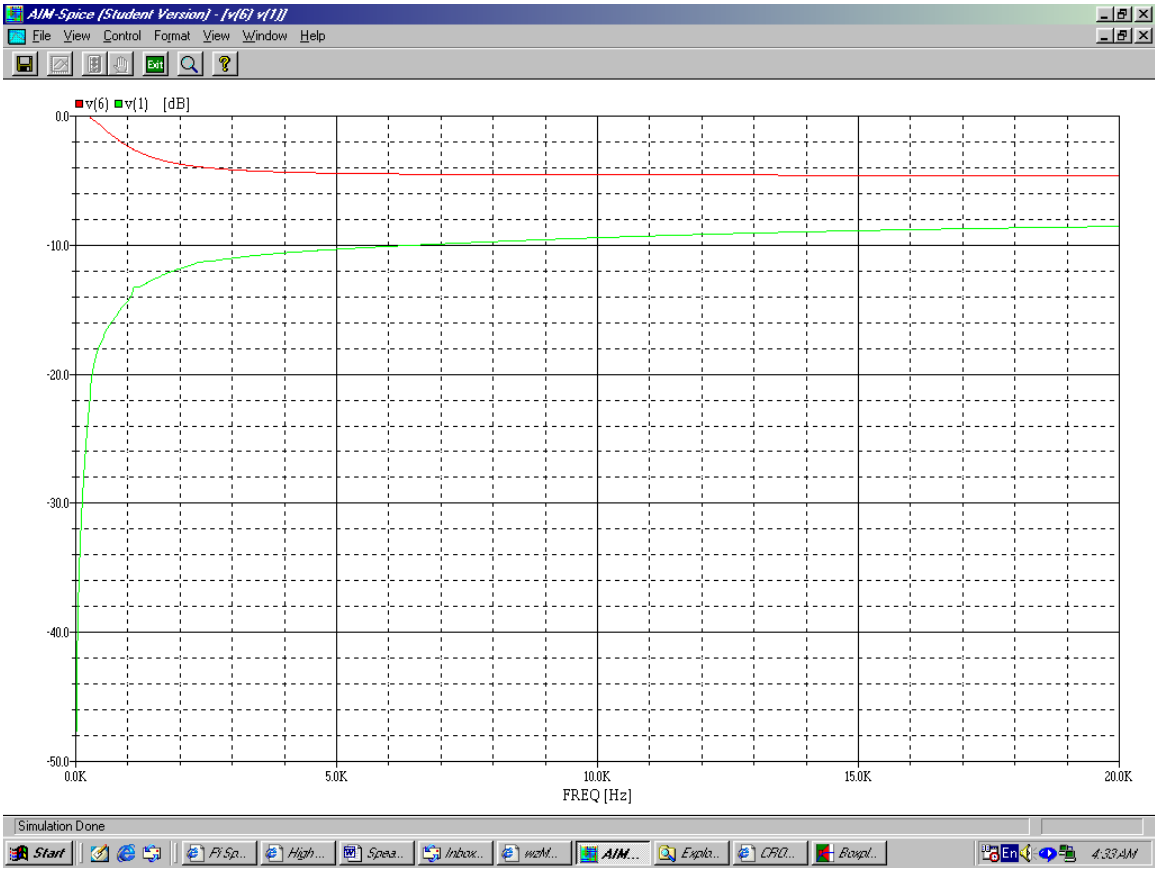
But while the resonator corrected the primary peak, it does nothing to affect the circuit to reduce the second or third peak. These cause a couple of 2dB anomalies around 1100Hz, and some smaller issues around 2200Hz. And the attenuation of this circuit is excessive for use with the Delta 15 – it was just done to demonstrate *peaking* with different values.



So we might want to take a moment to examine our other options. *There is another way to correct tweeter resonance anomalies, and it does not require dependence upon electrical resonators.*

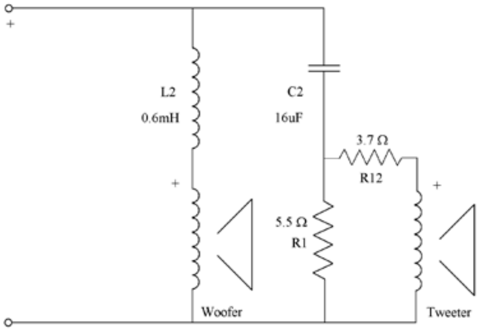
We can use another form of compensation network and remove our resonator. Let's install a series resistance and a parallel resistance to provide attenuation. The voltage divider then becomes fundamentally between the two fixed resistors instead of being between the single series attenuator and the tweeter.

So to effect the same 10dB attenuation, we might choose to replace the single series 15 Ω resistor with a series/parallel divider network of 5.5 Ω and 3.7 Ω.



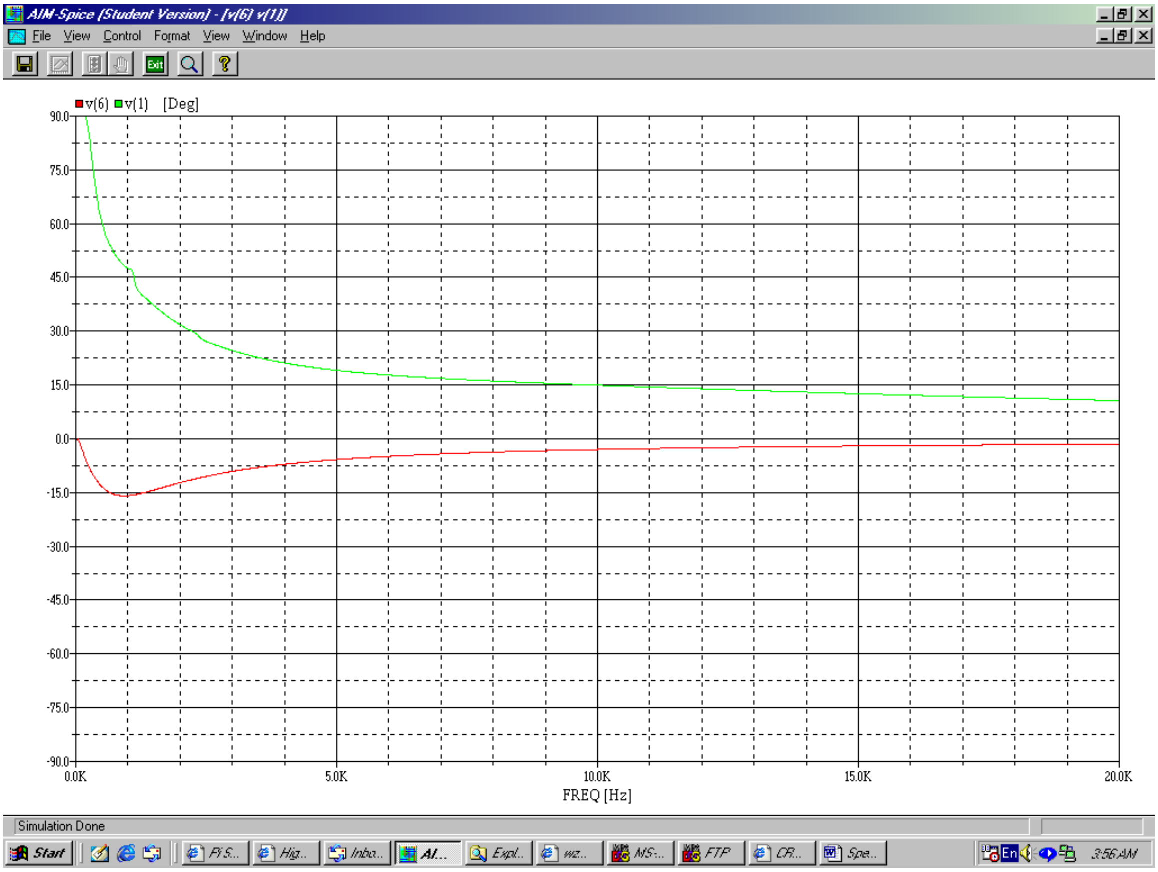
**Delta 15 and PSD2002 with 10dB series/parallel attenuation for the tweeter**

This provides excellent damping for the tweeter, removing the peaking effect at the tweeter horn's resonant frequency *without using an electronic resonator*. This form of series/parallel compensation network is known as a *resistor damped compensation network*.



```
! First order network
  L2      5     6     0.6mH
  C2      5     3     16uF
! series/parallel Compensation components
  R1      3     1     5.5
  R12     1     0     3.7
```

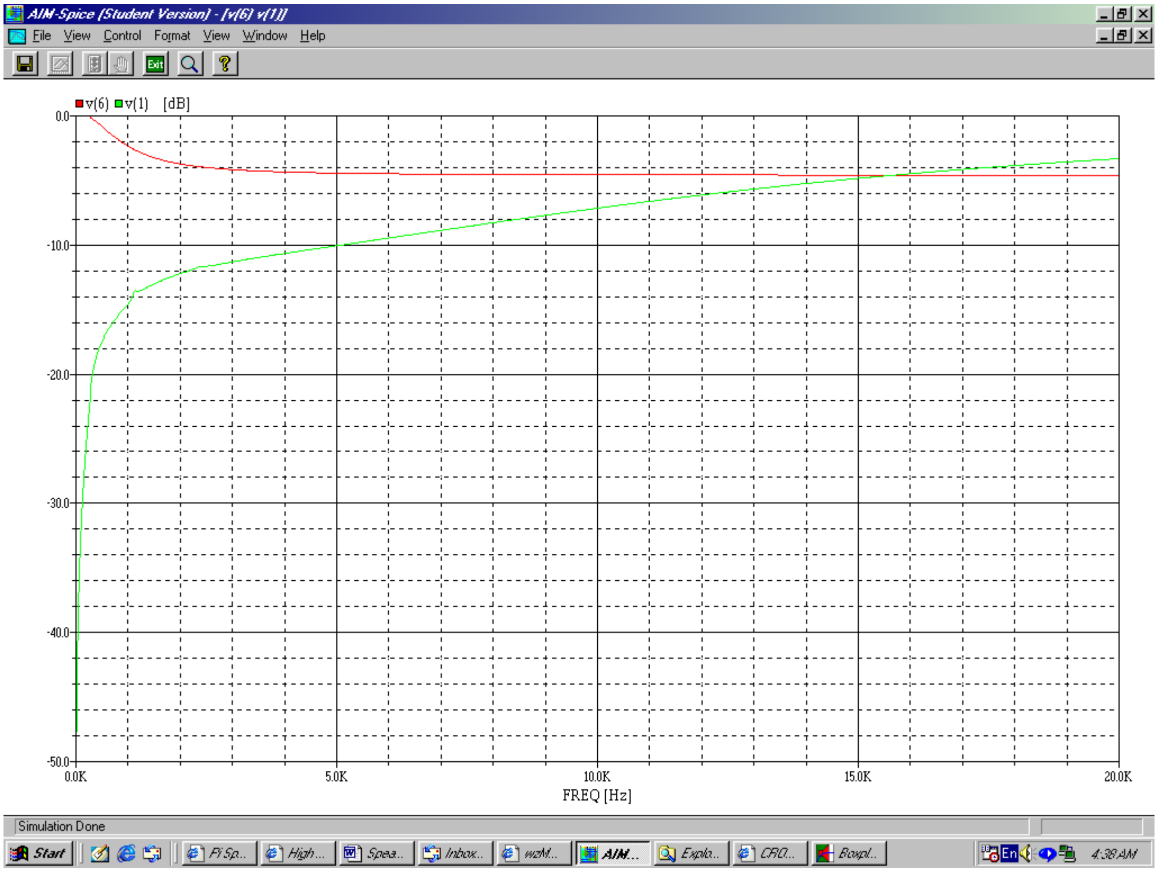
Now let’s examine the phase of this filter topology:



**Phase response of first order network with series/parallel attenuation**

A very similar phase curve to the previous network containing a resonator. This indicates that the damping provided by the resistor-damped attenuator performs similarly to the undamped filter having a resonator. Two very different approaches with similar results.

Now let's add compensation for the top octave, installing a 5μF capacitor across the 5.5Ω resistor.

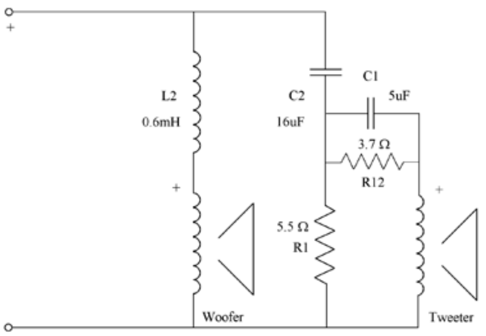


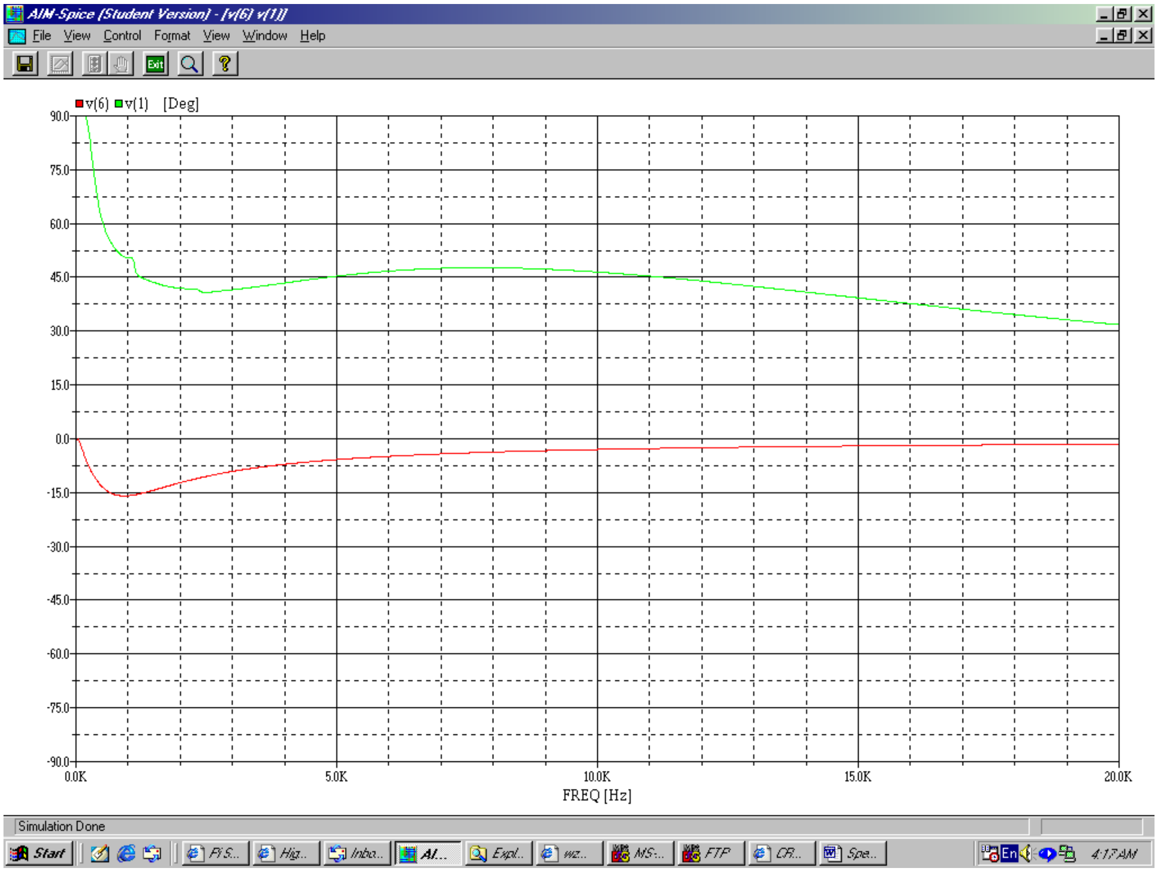
**Delta 15 and PSD2002 with compensation network**

This is a good curve for the tweeter circuit, and one that offers substantial performance benefits compared with an uncompensated design. It also benefits from the fact that there is no tank circuit across the tweeter to "tame" its impedance peak at horn cutoff – instead the reactance of the tweeter horn system is damped by the compensation components. But it does suffer from being about 3dB lower than desired at the crossover frequency, and is in effect, overdamped there.

The Spice circuit is as follows:

```
! First order network
  L2      5    6    0.6mH
  C2      5    3    16uF
! series/parallel Compensation components
  R1      3    1    5.5
  R12     1    0    3.7
  C1      3    1    5uF
```





**Phase response of first order network with series/parallel compensation**

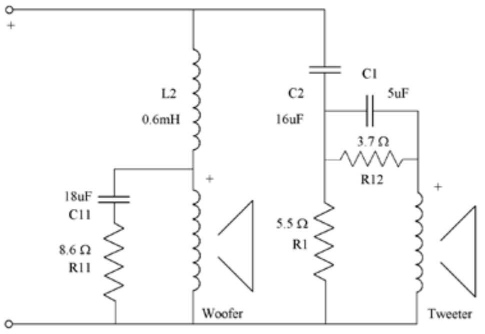
Notice that the resistor damped compensation network keeps tweeter phase near to 45 degrees through its passband, just like the series compensator did. Phase of the resistor-damped network tends to fall at the very top frequencies, and is 30 degrees at 20kHz.

The series compensation network provided some peaking from the reactive components that resonated at cutoff. It had both resonant systems that peaked at horn cutoff and those that damped them, similar to the way a bass reflex system works using two resonators at close frequency.

But this solution is more like an acoustic suspension system having static damping. It is damped over a broader range of frequencies, and cannot be used for controlled peaking, so the entire bottom region of the response curve is damped.

At 10kHz, the curve is up about 3dB over unity but by 20kHz it is only up about 6dB over unity. So this design could be improved slightly, *by removing some damping and allowing a small amount of peaking to occur.*

Also, the Delta 15 produces significant output above the expected crossover frequency. We need to reduce the energy developed across the woofer, and this may be accomplished using an RC damper for the woofer.

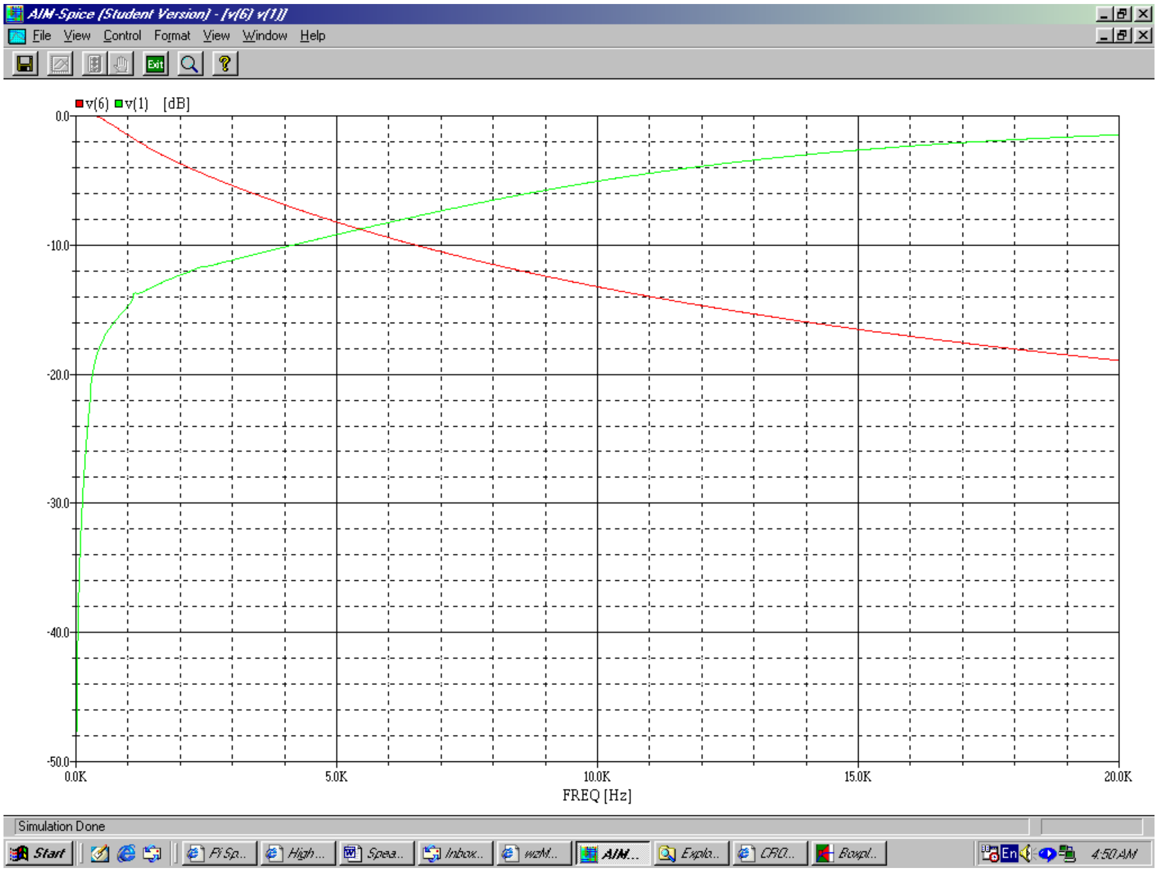


The formula for calculating an optimal RC damper is:

$C_z = L_e/R_e^2$ or $18\mu F$

$R_z = 1.25R_e$ or $8.625\ \Omega$

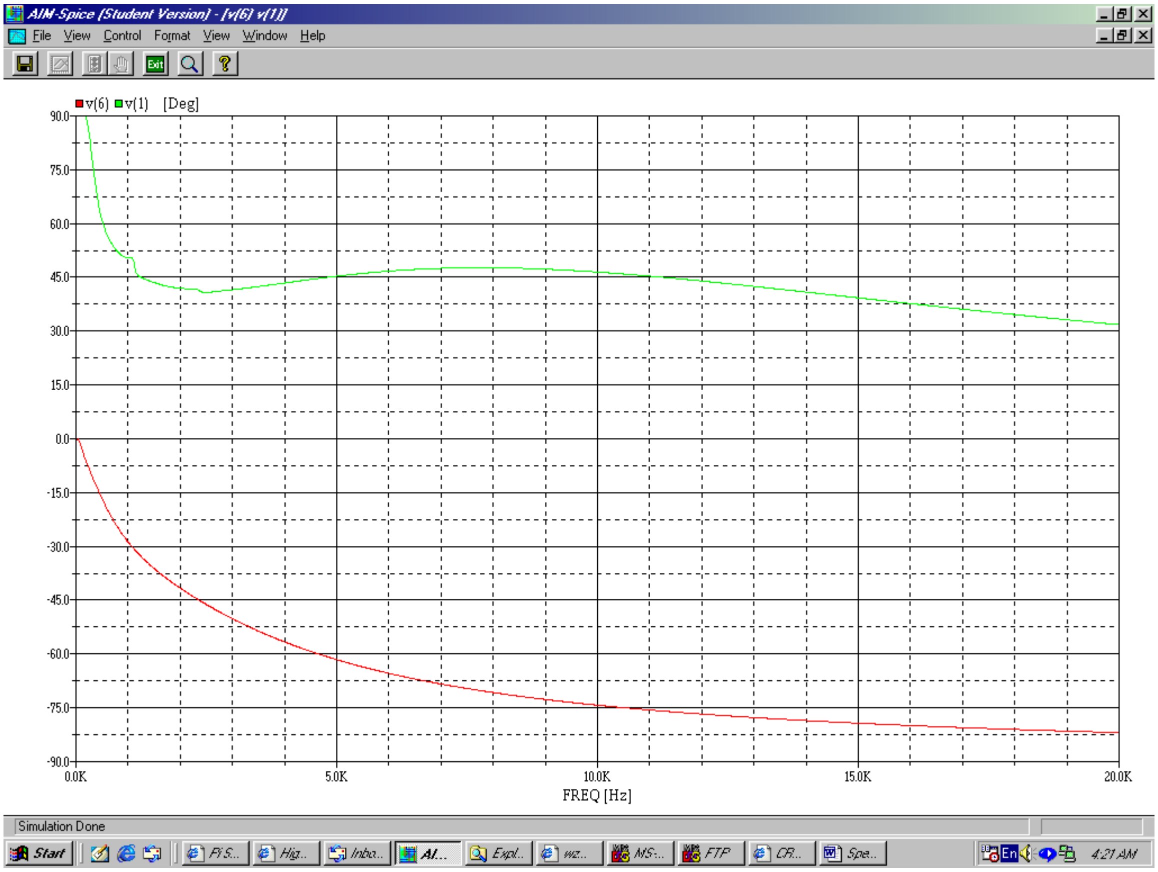
So let's insert an RC damper and investigate system performance.



**Delta 15 and PSD2002 with compensation network and RC damper**

This is a completed design, optimized as much as is possible for a first order crossover. It may look like it is designed for 5kHz crossover, but this just happens to be where the lines cross. Remember that the PSD2002 is 9dB louder than the Delta 15, and the green line representing the tweeter curve is then shifted upward by 9dB. The woofer (in its cabinet), tweeter and this crossover response curve should be algebraically summed to graph the system response curve.

Let’s examine phase of this optimized first order filter:



**Phase response of first order network with compensation and RC damper**

Woofer phase clearly shows that it is now acting as expected, with phase around 45 degrees at crossover and approaching 90 degrees at its asymptote (maximum into the stopband).

**This is a fully optimized first order network.** It appears that the series compensation network and the resistor-damped network each provide equivalent performance, but the series offers a little better peaking, or the so-called “step” response. That is attractive, since what we really want is a flat curve from 1.6kHz to 4kHz, and then a gradual rise after that. But the resistor-damped configuration is attractive because no additional reactive components are required.

An RC damper or “Zobel” is great for offsetting reactance issues from rising impedance in the upper bounds of a driver’s response curve. And a tank circuit equivalent to the motors resonant characteristics is great for removing the “Zmax” impedance peak at resonance.

But problems arise with these types of corrective filters.

1. The rising impedance of the tweeter is not important to the discussion, so an RC damper is really only an attractive possibility for the woofer.
2. The proper implementation of an RC damper for a woofer requires the use of physically large devices.
3. Proper implementation of an electronic damping resonator for impedance correction of the woofer’s “Zmax” impedance peak also requires the use of physically large devices.
4. The resonant frequency of a bass subsystem is affected by its cabinet. If the system is acoustic suspension, then resonance is shifted upward by a predictable amount. In this situation, an electronic resonator is most appropriate as an impedance compensating tank circuit. But in a bass reflex cabinet, there are two impedance peaks and, while predictable, implementation of two tank circuits is less attractive. And in a bass horn, there are multiple peaks making the choice of a tank circuit or a system of tank circuits rather unattractive.
5. This situation is similar for the tweeter horn. A single tank circuit cannot reliably correct its impedance in the crossover region, because there is a multiplicity of impedance peaks in this region. The tweeter diaphragm and at least two horn-induced events are participating in the HF horn’s impedance in the crossover region. *This is true even for systems tuned over one full octave above horn cutoff, and two full octaves above motor cutoff.*

A few conclusions are then evident:

1. An RC damper may be productive for correction of the woofer’s upper frequency impedance rise, but it cannot be considered useful for correction of the impedance peak at resonance.
2. The “Zmax” peak at resonance of a woofer is too low to negatively affect a crossover filter configured to be active five octaves later.
3. An electronic resonator is not attractive for correction of bass reflex or bass horn impedance peaks at resonance because there is more than one resonant peak. A damping resistor might be considered instead.
4. The impedance rise of a tweeter is at too high a frequency to negatively affect a crossover filter configured to be active several octaves earlier.
5. The RC damper is not attractive for correction of a tweeter’s impedance rise at higher frequencies, because the damper may attenuate the tweeter in the top octave. The impedance rise of the tweeter does not affect performance of the crossover filter, so the damper has no effect anyway.

6. A resonator is not attractive for correction of a horn tweeter's multiple impedance peaks near the crossover frequency. For this option to be realistically considered, no fewer than three tank circuits would need to be employed. Damping resistance is preferred instead.

As an aside, when using a woofer having high voice coil inductance and reduced output at upper frequencies near cutoff, the uncompensated curve shown in all previous response curves is optimal. In this configuration, the inductor used as a woofer "crossover" filter does not act as a filter at all, because woofer impedance rises exactly as the filter does. When woofer inductive reactance nears that of the filter coil chosen, the crossover coil should be considered a "Pseudo First-Order" even if the value chosen appears to be appropriate.

The JBL 2226 can be used for such an implementation. One look at the response curve of a JBL 2226 shows that it generates very little output above 1.6kHz, and the speaker sounds clean up through the midrange. So a tweeter circuit that is designed to bring it online between 1kHz and 2.0kHz blends very well with these woofers – even with no woofer crossover at all. However, it is also evident that there is a slight increase in output just below upper cutoff, and this is reduced by adding inductance to the system.

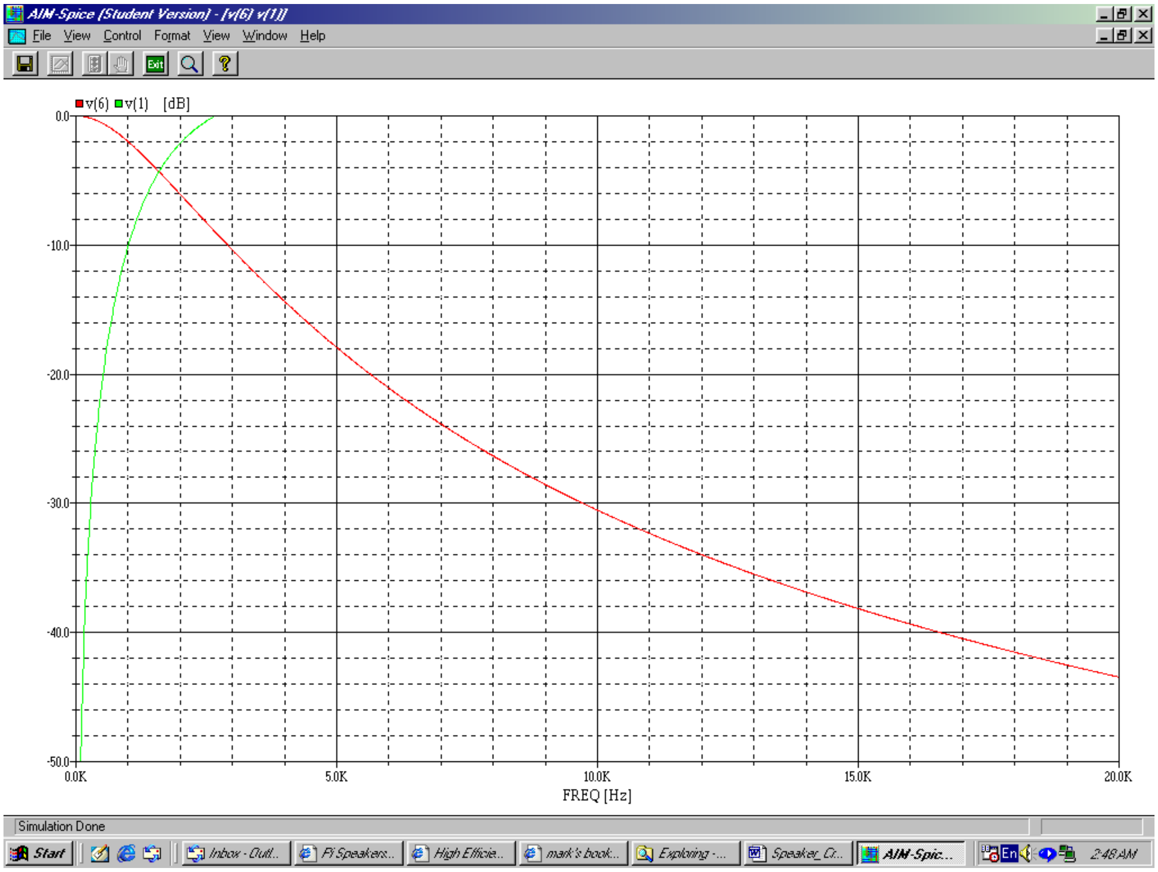
Such a system is called a "Pseudo First-Order" filter, because output is reduced above a certain frequency, but it does not provide a 6dB/octave slope like one might expect when examining the schematic diagram. Maximum attenuation is limited to less than 6dB, and is often much less – depending on components chosen.

But in the case of the Delta 15 – which has cone flex resonances at fairly high frequencies – it is desirable to rolloff HF energies sent to the driver. We must either use a higher order network or use a compensation network for the woofer, or both.

There are a few areas that might be improved:

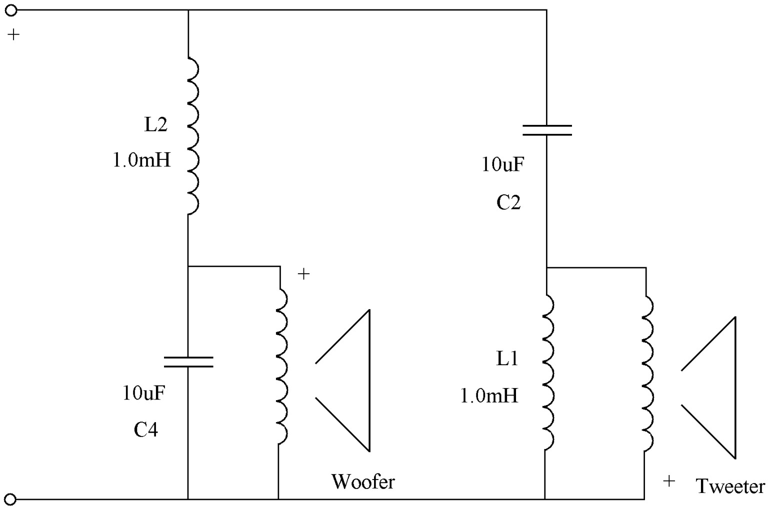
1. The tweeter curve is very good, but response is a little bit low in the octave above crossover. At 1.6kHz – the crossover frequency – we are 3dB too low and response isn't flat until over 3kHz. Also, at only 6dB/octave, it doesn't fall fast enough under the crossover frequency. Since attenuation is provided, it may be safe. But you will notice that power to the tweeter at 1kHz is only 2dB less than power at 2kHz and at 500Hz, it is only about 6dB lower than at 2kHz. This means that the tweeter is vulnerable in high output conditions.
2. Compensation resistors are very low values, so they must be able to conduct a lot of current. Very high power components are required for this design.
3. First order networks, by their nature, have a large overlap region. Their phase characteristics are good in and of themselves, but the nature of overlap and of the distance between drivers in three-dimensional space makes interference banding from diffraction much more problematic, particularly in high output loudspeaker systems.

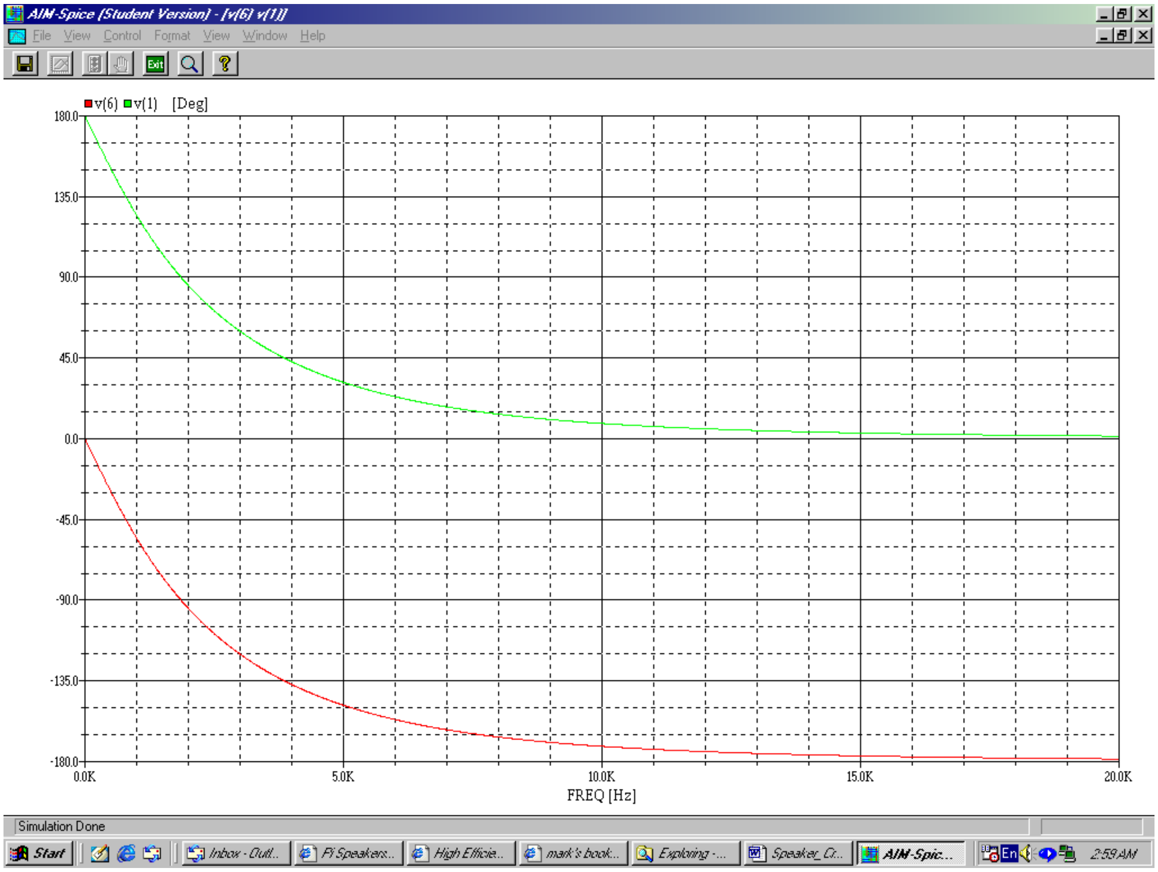
## Second Order Crossover



1.6kHz second order crossover

This is a second order crossover with simplified speaker motor loads of 6 Ω and 0.1mH. The response curves with idealized loads look great, but even without looking at this network with "real world" drivers a serious potential problem presents itself: ***Phase***

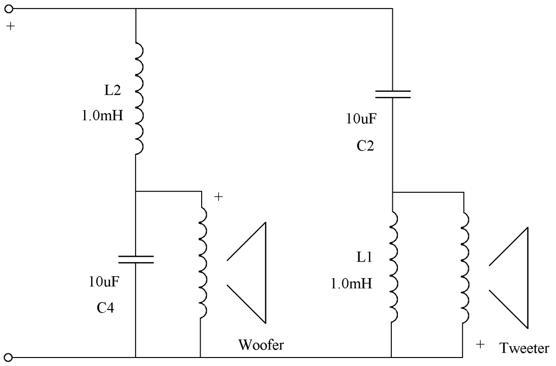




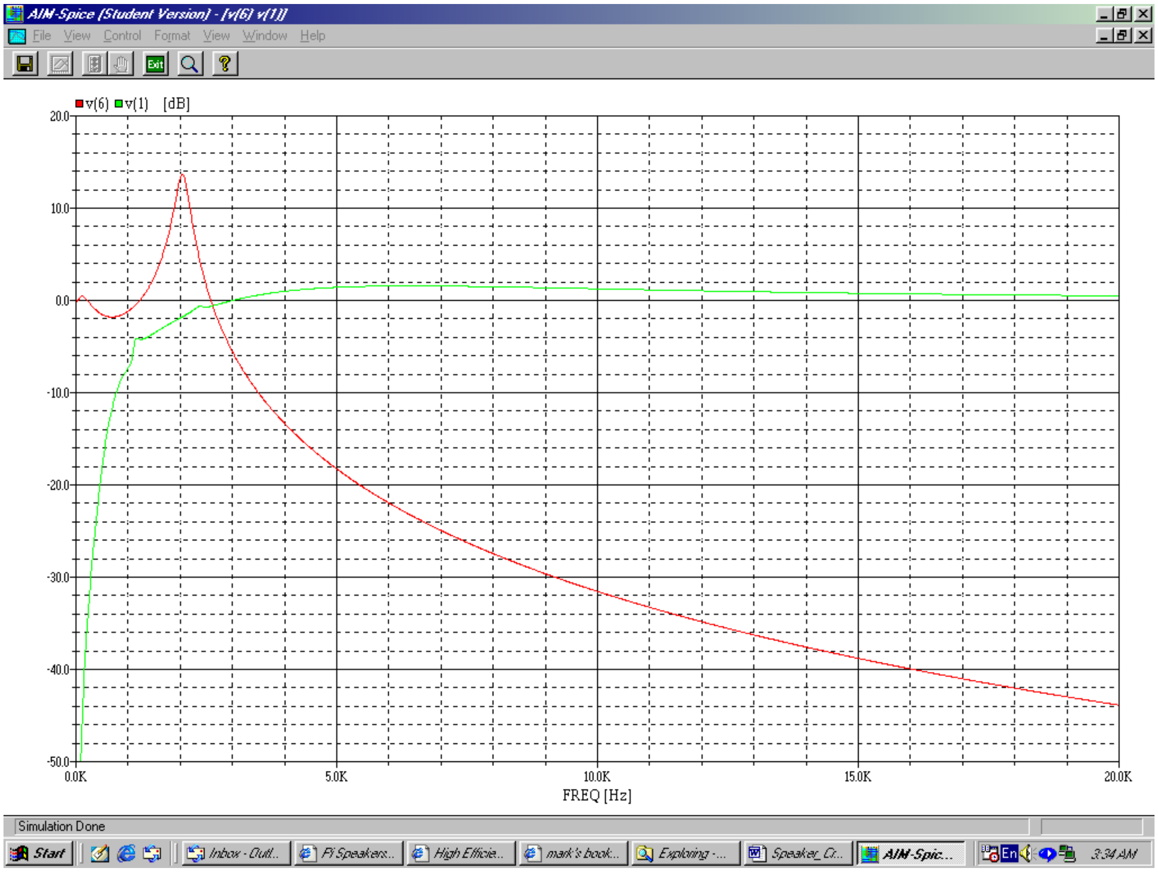
**Phase response of second order network**

As you can clearly see, the woofer and tweeter are 180 degrees out of phase over the entire audio bandwidth. This causes the two diaphragms to move 180 degrees out of phase and they will cancel each other through the overlap region.

*One solution is to "cross connect" the drivers.* Simply connect the tweeter in opposite polarity so that the phase reversal actually affects a phase correction.

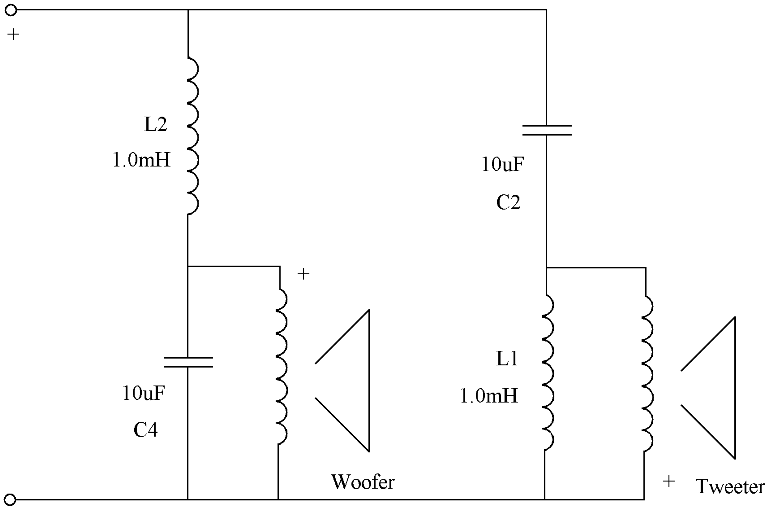


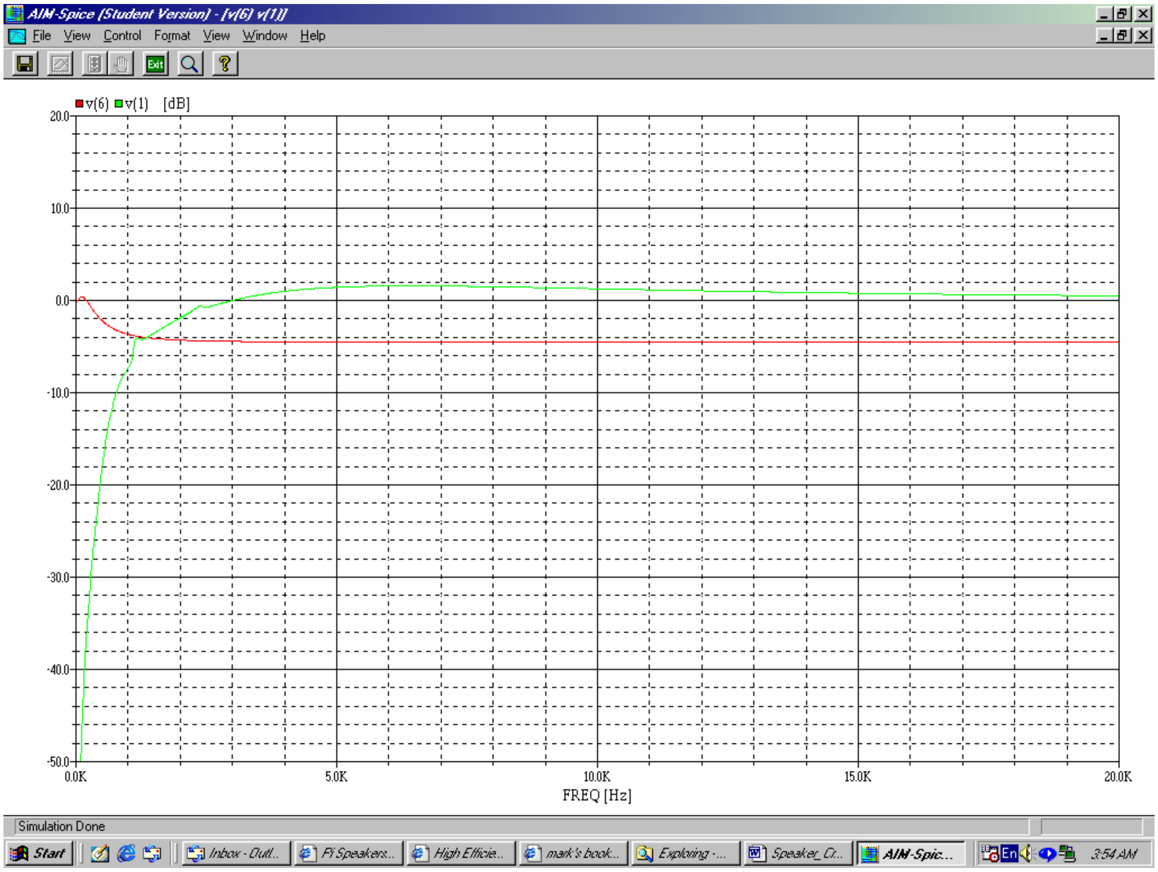
But now, let's connect some "real speakers" to our second order crossover.



**Delta 12LF and PSD2002 using second order network**

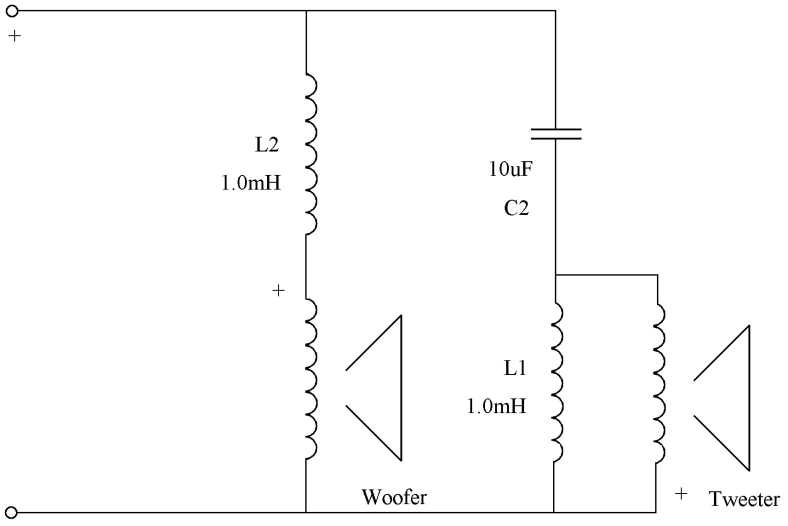
The second order filter is crippled when combined with a highly inductive load, such as the Eminence Delta 12LF. If the woofer has reduced output near the crossover frequency, then it may be a good candidate for using a "Pseudo First-Order" filter for the woofer – by simply removing the capacitor across the woofer.



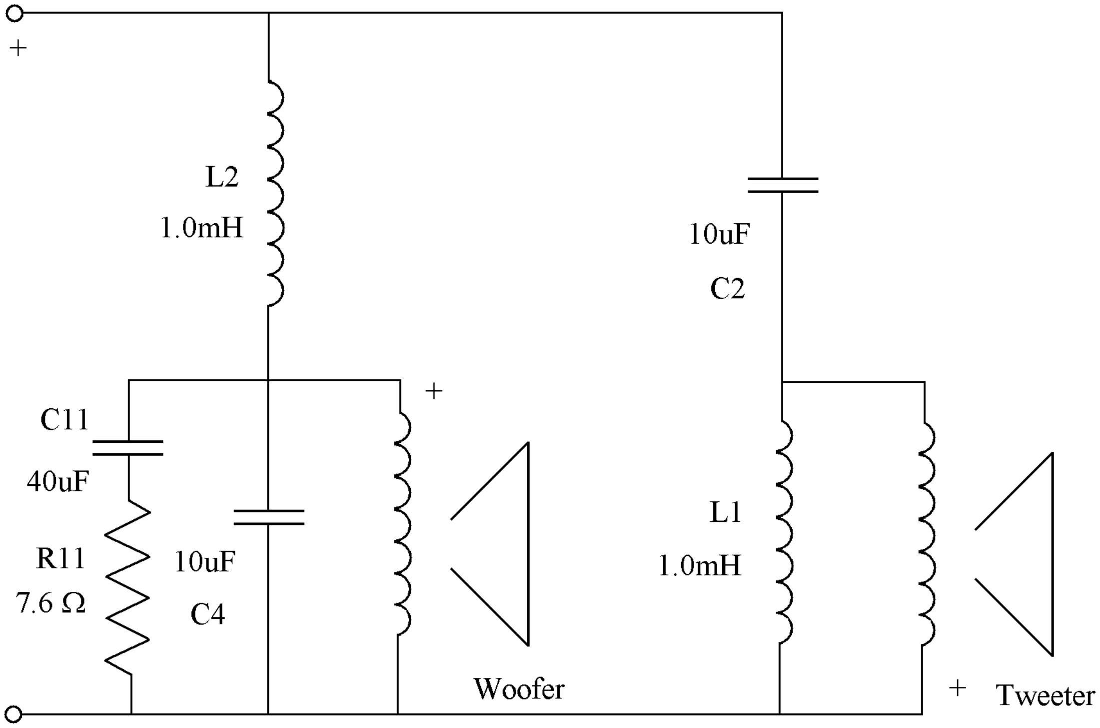


**Delta 12LF and PSD2002 using second order tweeter filter and "Pseudo First-Order" woofer filter**

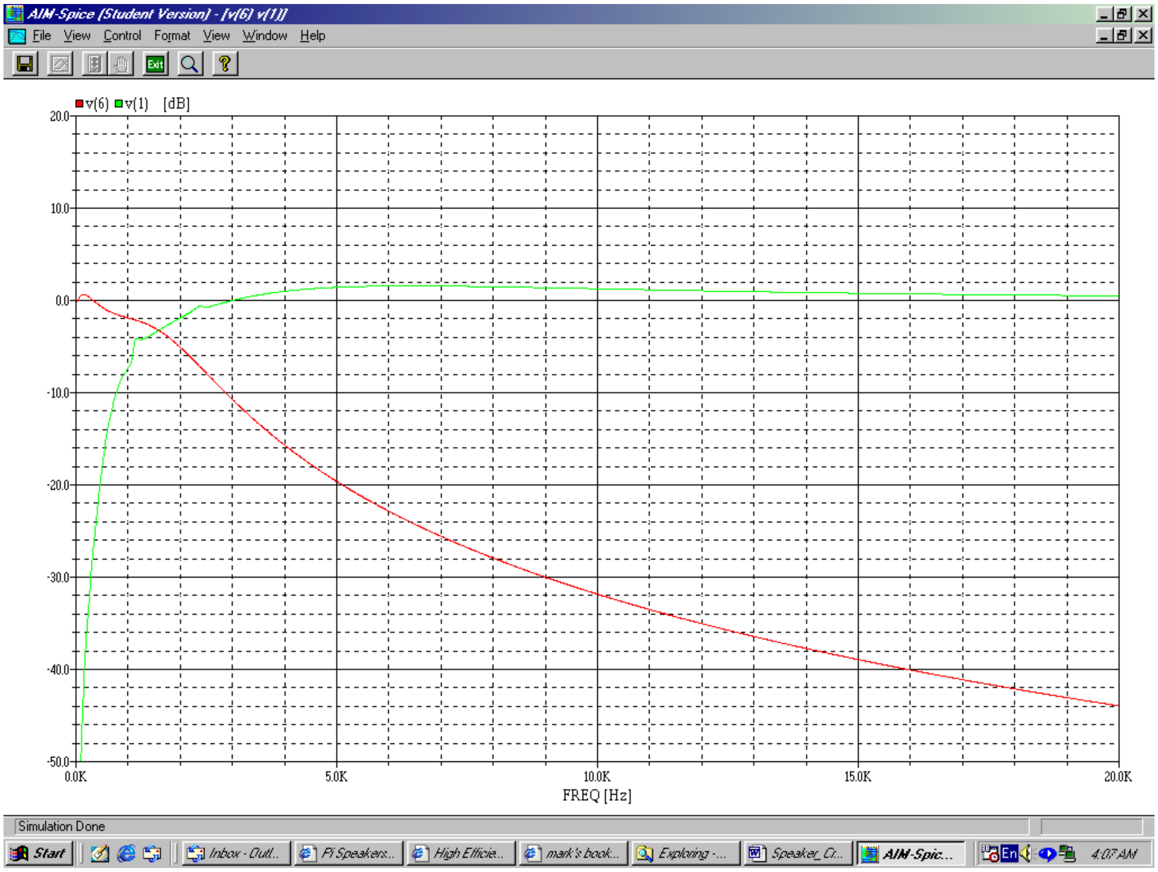
Simply removing the capacitance from the woofer circuit removes the 14dB peak. But now attenuation is only about 4dB at the crossover frequency.



Let’s connect a Zobel RC damper instead.

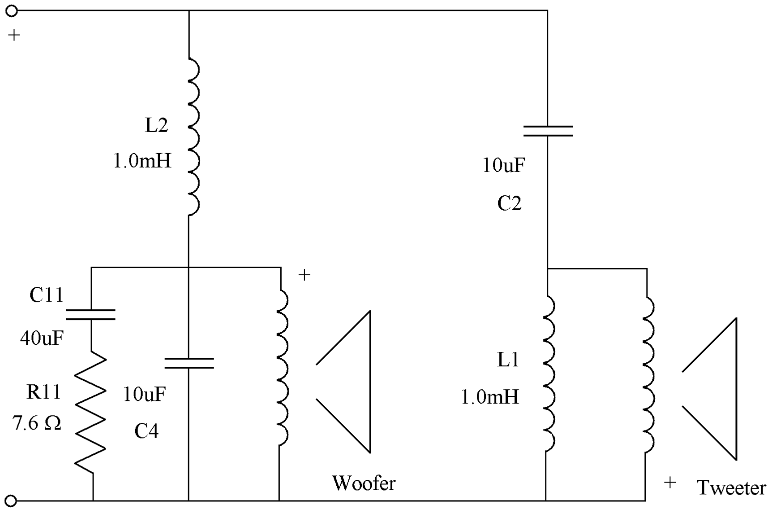


**Delta 12LF and PSD2002 with second order and RC damper for woofer**

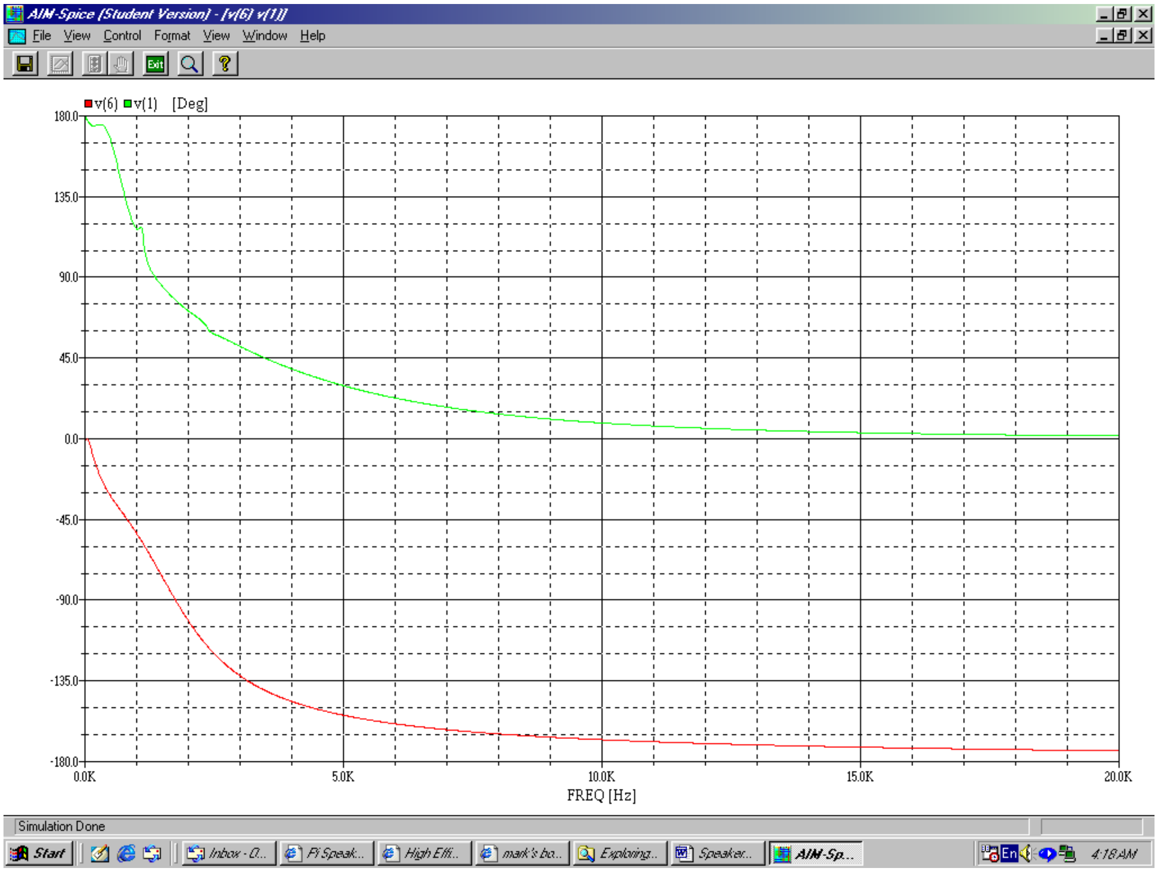


**Delta 12LF and PSD2002 with second order and RC damper for woofer**

A 7.6 Ω resistor in series with a 40µF capacitor was installed as a Zobel woofer damper. This provides a significant improvement over an uncompensated network.



Let’s examine the phase of this network.



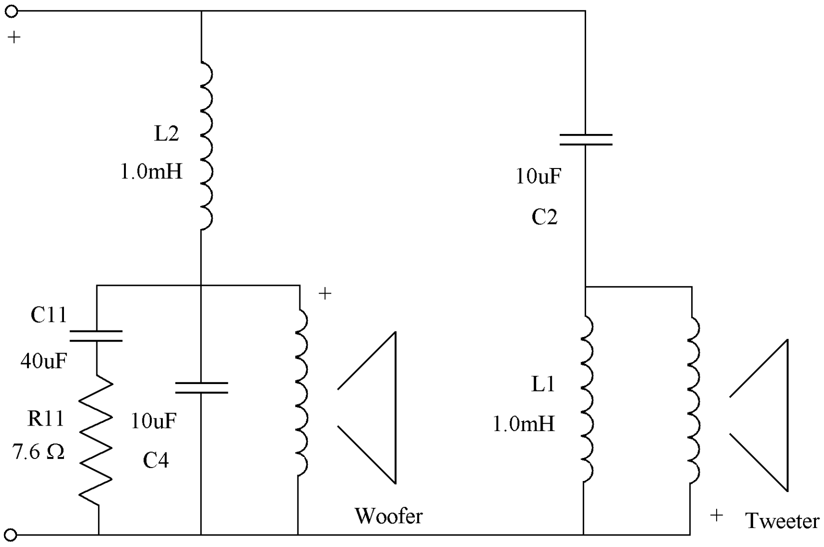
**Phase response of a second order network with RC damper**

The phase response of this system is very similar to the idealized second order network.

Spice model:

```
! woofer virtual circuit (Eminence Delta 12LF)
! voice coil reactance
  R3        6       7       6.06
  L3        7       9       1.45mH
! mechanical reactance (45Hz, Q=7.28)
  C5        9       14      350uF
  L5        9       14      35mH
  R5        9       14      72.8
  ported cabinet (30Hz, Q=1.22)
  C10       14      0       520uF
  L10       14      0       52mH
  R10       14      0       12.2
```

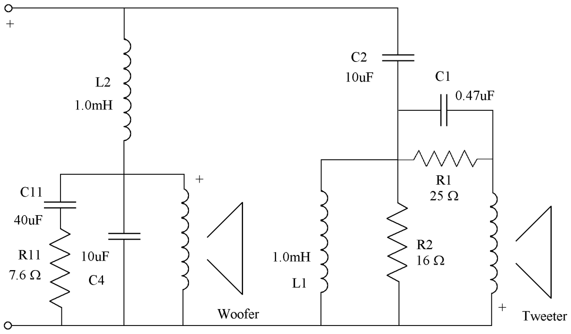
```
! tweeter virtual circuit (Eminence PSD2002)
! voice coil reactance
  R4      1     10    6.6
  L4      10    11    0.1mH
! mechanical reactance (on H290)
  C6      11    12    20uF
  L6      11    12    2mH
  R6      11    12    100
  C7      12    13    10uF
  L7      12    13    1mH
  R7      12    13    100
  C8      13    0     5uF
  L8      13    0     0.5mH
  R8      13    0     100
  R9      11    0     20
  C9      11    0     50uF

! Crossover Network
! second order woofer network
  L2      5     6     1.0mH
  C4      6     0     10uF
! second order tweeter network
  C2      5     1     10uF
  L1      1     0     1.0mH

! RC damper for woofer
  R11     6     17    7.6
  C11     17    0     40uF
```

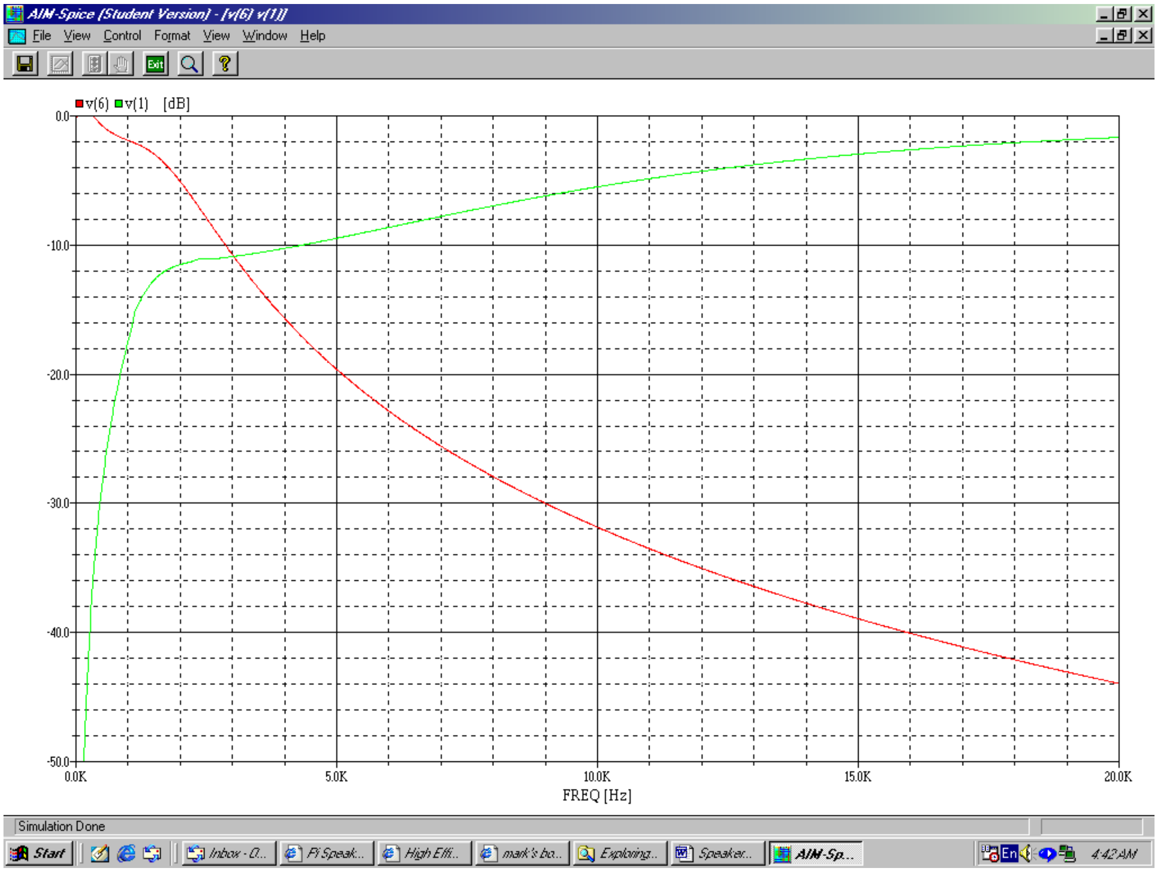


Now, let’s add the appropriate tweeter compensation. The Delta 12LF generates about 97dB@1W/1M at the crossover point. So the PSD2002 device on the H290 should be attenuated 13dB, and top octave compensation employed as well.

So let’s add this compensation to the system:

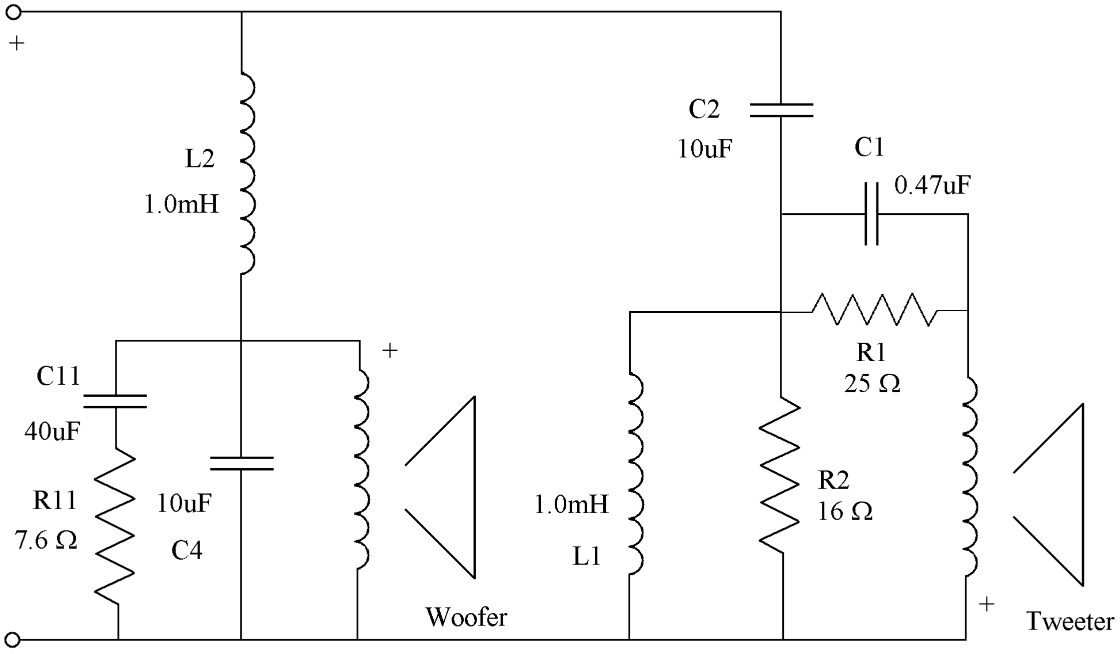
```
! series/parallel compensation
  R1        3      1      25
  R2        1      0      16
  C1        3      1      0.47uF
```





Simulation Done

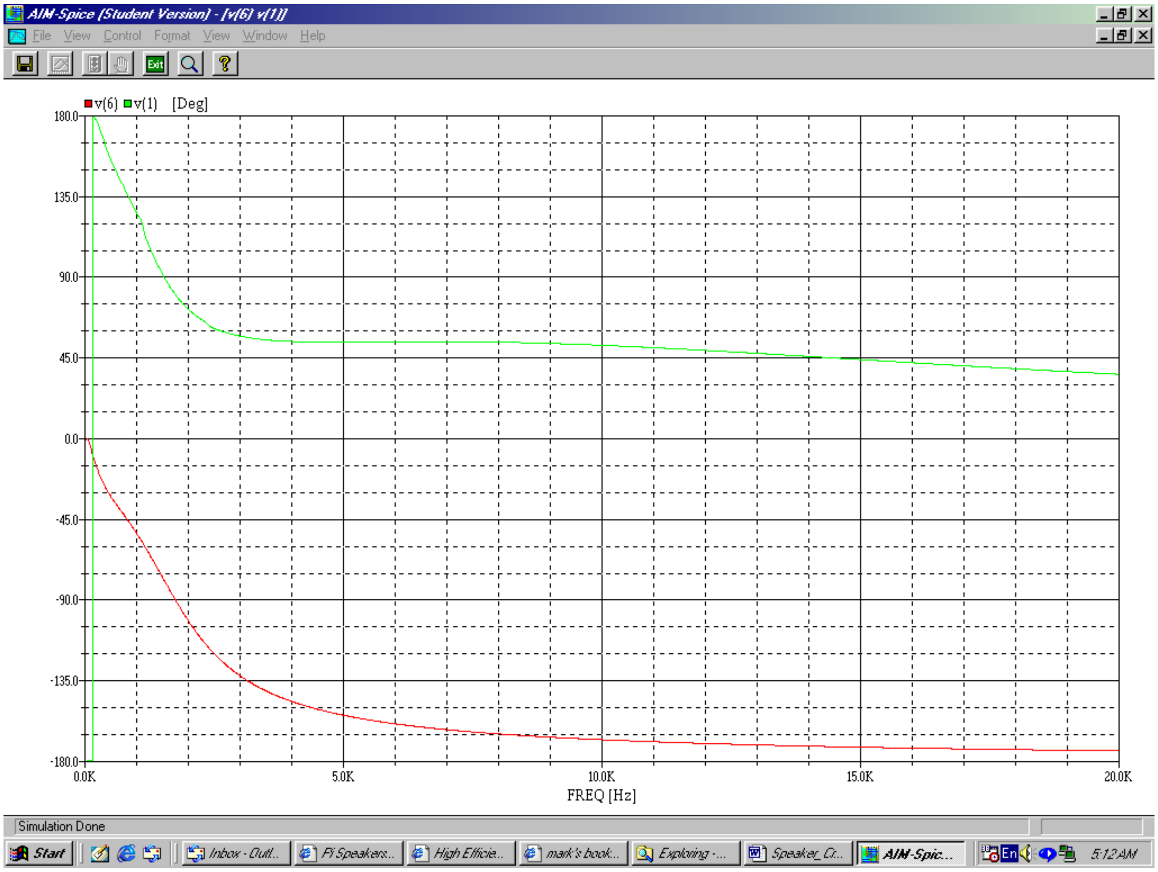
Delta 12LF and PSD2002 with compensation network



**This is a fully optimized second order network.** It consists of a 10µF capacitor and a 1.0mH inductor for each motor. The woofer circuit also has an RC "Zobel" damper consisting of a 40µF capacitor and 7.6 Ω (or 8 Ω) resistor. And the tweeter circuit has a 12dB compensation network consisting of 25 Ω, 16 Ω and 0.47µF components.

The response curve of this network is very good, with the woofer circuit being around unity up to 500Hz, where it begins to fall. Response is –3dB at 1.6kHz and –12dB at 3.2kHz, so these are "textbook" figures. And the tweeter circuit is –12dB at 1.6kHz and –24dB at 800Hz. Since the tweeter circuit has been attenuated –12dB, these power levels are offset by this amount and the tweeter circuit is acting as expected. Between 1.6kHz and 4.8kHz, response only rises 2dB to –10dB, so the tweeter circuit is reasonably linear in the midrange. From 5kHz, response rises at the rate of approximately 6dB/octave.

Now, let’s look at the network’s phase response.

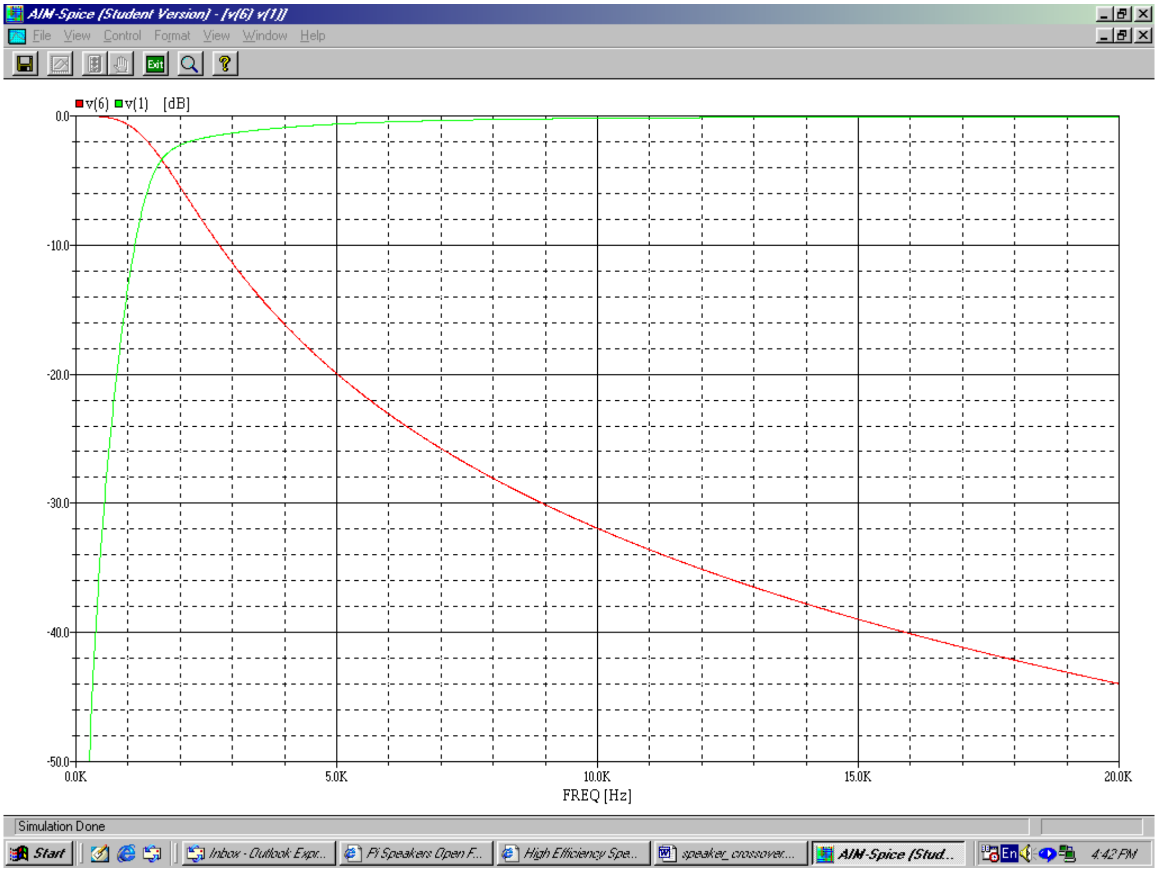


**Phase response of second order network with compensation**

Phase response of this network is easy to understand. It has the second order phase curve from low frequencies through the crossover frequency, and it remains the same as the “idealized network” until approximately 3.2kHz, where tweeter compensation begins to modify phase exactly as we’ve seen before – maintaining tweeter phase at approximately 45 degrees.

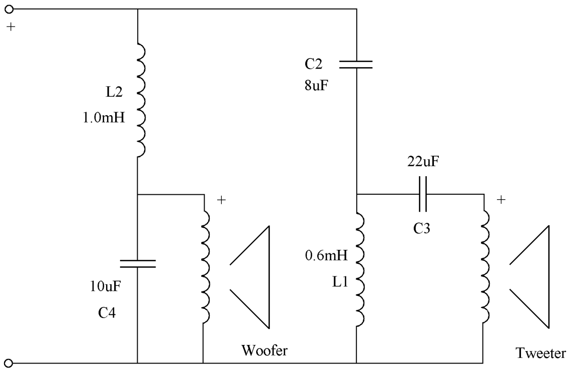
The most important thing to understand when using this crossover network is that it uses contiguous second order filters, so the woofer and the tweeter must be *cross-connected*. Failure to do so will ensure that there is a huge negative spike at 1.6kHz, often as much as 30dB – depending on driver placement. But the solution is simple and effective – Just connect the tweeter so that its positive lead is connected to the woofers negative lead in a manner that appears to be out of phase. Then, since the crossover filters shift the woofer and tweeter 180 degrees from one another, the crossover region will be additive rather than destructive.

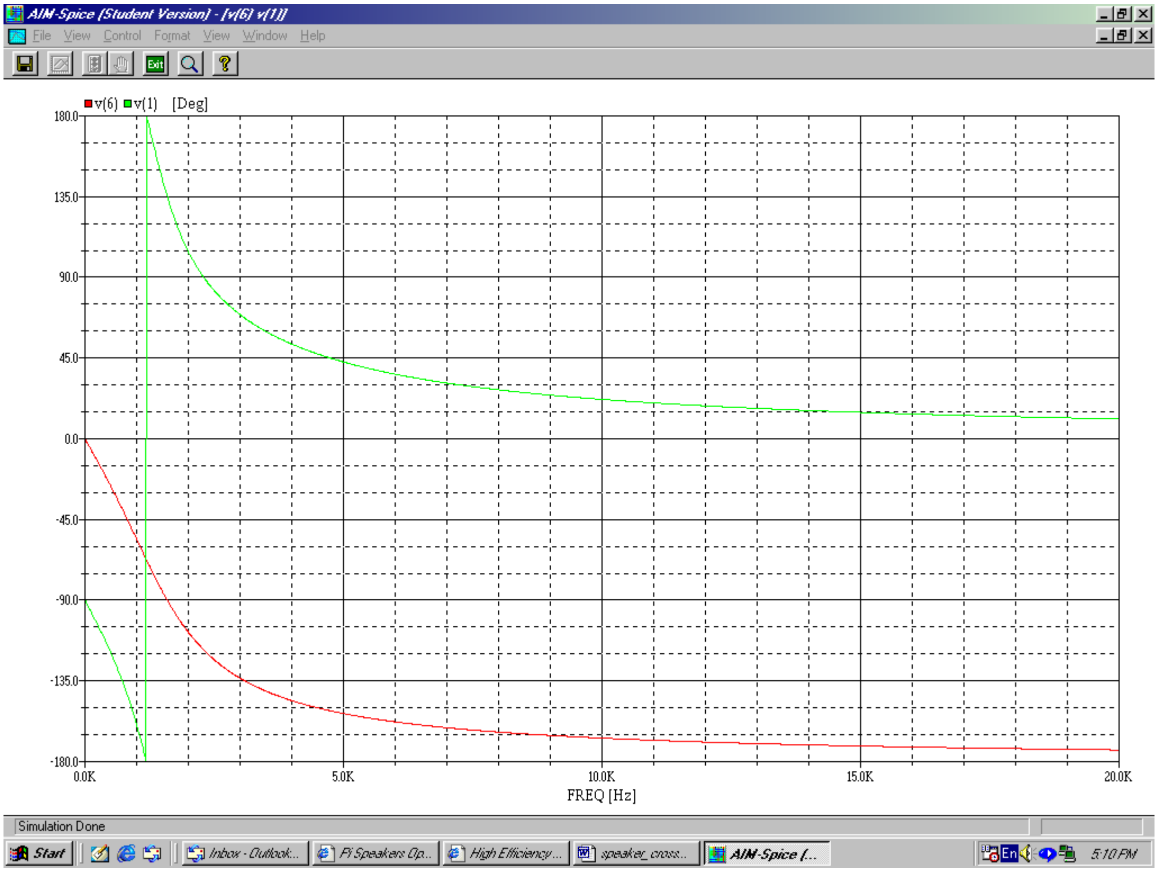
Since contiguous second order networks create 180-degree phase shifts between motors, an obvious solution is to change the topography of at least one of the filters. Third order filters do not modify phase by 90 degrees at the crossover frequency, so the use of contiguous filters cannot result in perfect phase alignment either destructive or additive.



**1.6kHz crossover using third order high pass and second order low pass**

This is the response curve of a crossover having second order woofer filter and a third order tweeter filter. Most π Speakers have a crossover that uses this topology for its "base network."

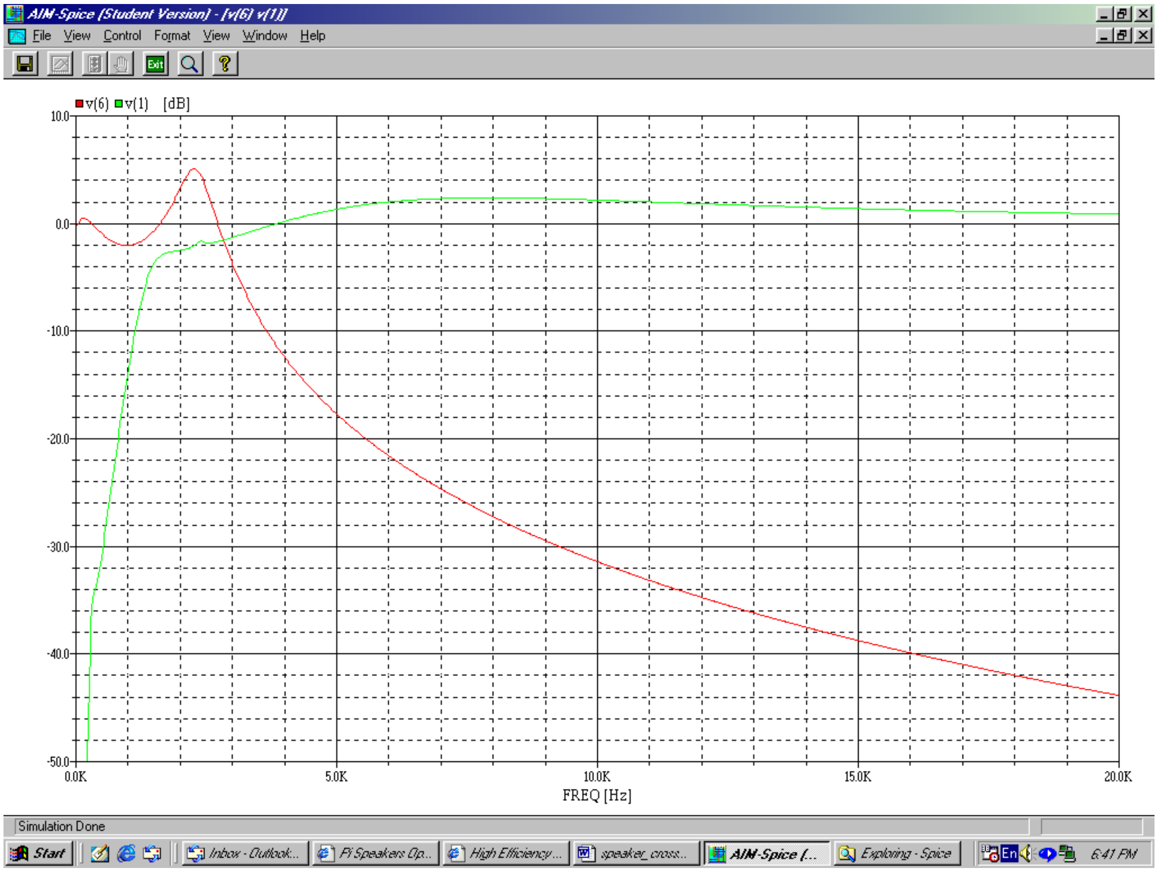




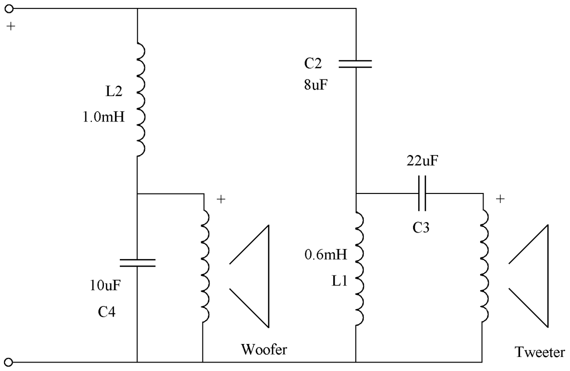
**Phase response of crossover having third order tweeter and second order woofer**

As you can see, the woofer is in phase at the lowest frequencies, and then falls to being 90 degrees behind at the crossover frequency, approaching its 180-degree asymptote in the stop band.  The tweeter is shifted 270 degrees ahead at the lowest frequencies and falls to being in phase as it enters its passband.  Tweeter phase is 135 degrees ahead at the crossover frequency.

Now let’s include actual speaker motors in the circuit.



**Alpha 12 and PSD2002 using second/third order network**

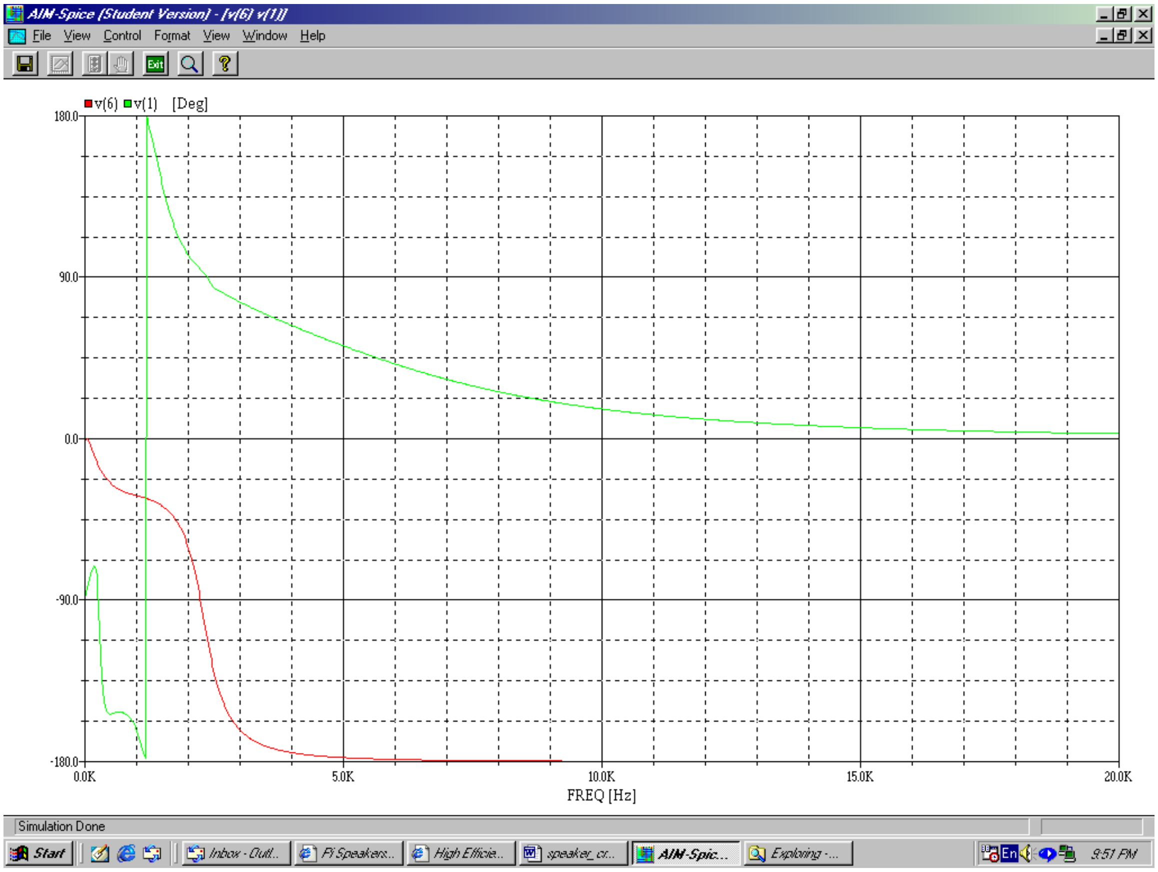


The tweeter circuit of this crossover uses a third order slope having values of 22uF/0.6mH/8uF and the woofer circuit has the same 1.0mH/10uF second order network as the preceding purely second order example did. But this implementation of the filter with an Alpha 12 woofer doesn’t have nearly the peak that the same filter had with the Delta 12LF.

Compare this response graph with that shown on page 45. Clearly the peak around 2kHz is not as troublesome when using the Alpha 12 as when using the Delta 12LF. The Delta woofer has a peak of 14dB at 2kHz with this filter, but the Alpha only has a 5dB peak with the same network. In both cases, the tweeter has a response dip of approximately 2dB at this frequency which tends to compensate. This is significant, since it is above the crossover frequency and where the tweeter is expected to be fully on-line.

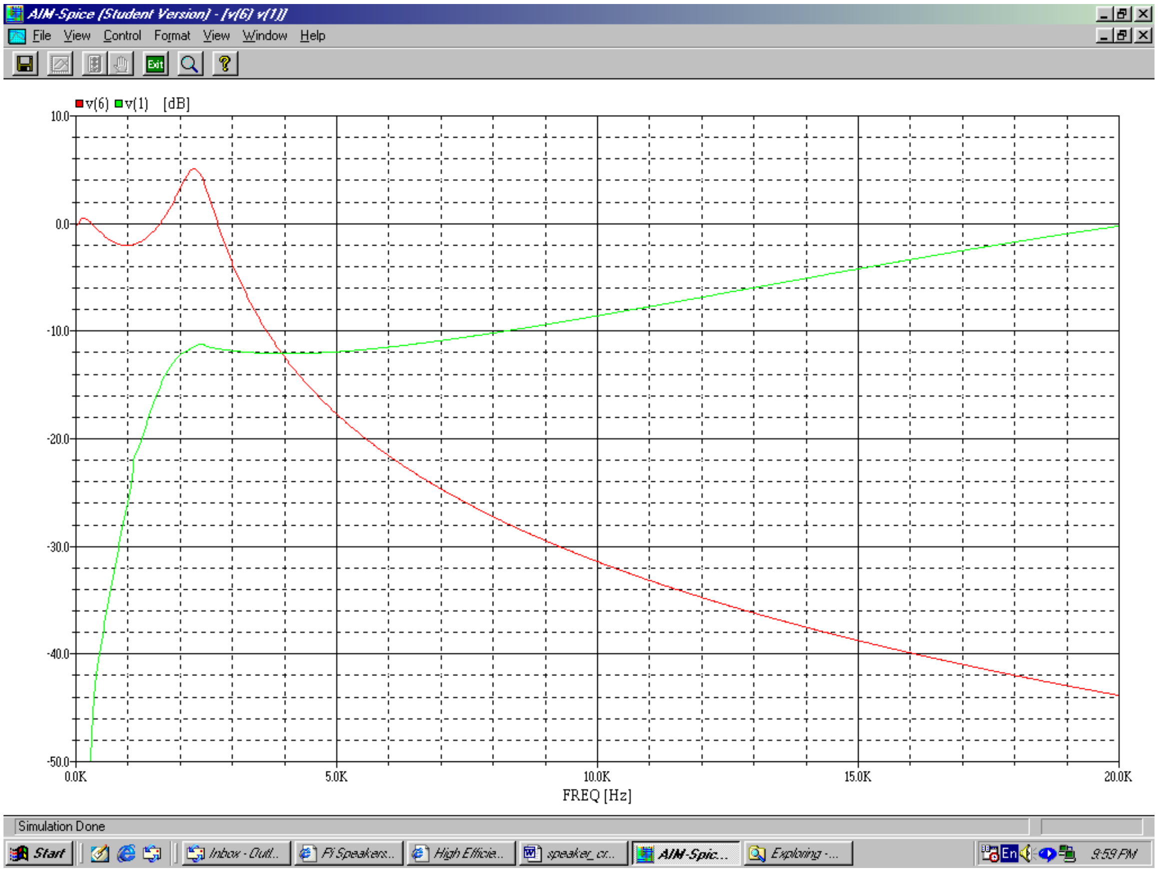
In the former case – the Delta 12 – the peak at 2kHz is of such great amplitude that the anomaly is evident. But in this case – the Alpha 12 - the woofer anomaly is much smaller and tends to counteract the tweeter anomaly, making the system relatively linear without additional woofer compensation.

The reason that the Alpha 12 has so much less need for woofer compensation than the Delta 12LF is that voice coil inductance is quite different. The Delta 12LF has more inductance than the crossover and the Alpha 12 has less. Specifically, the Delta 12LF voice coil is 1.45mH and the Alpha 12 voice coil is 0.8mH. So a good "rule of thumb" is that woofer compensation RC damper circuits may be omitted if voice coil inductance is less than crossover inductance.

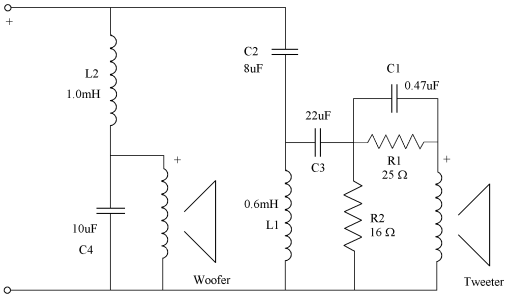


**Phase response of Alpha 12 and PSD2002 using second/third order network**

Since the tweeter is 12dB louder than the woofer, we'll install the same 12dB compensation network as was used with the system containing a Delta 12LF and PSD2002.



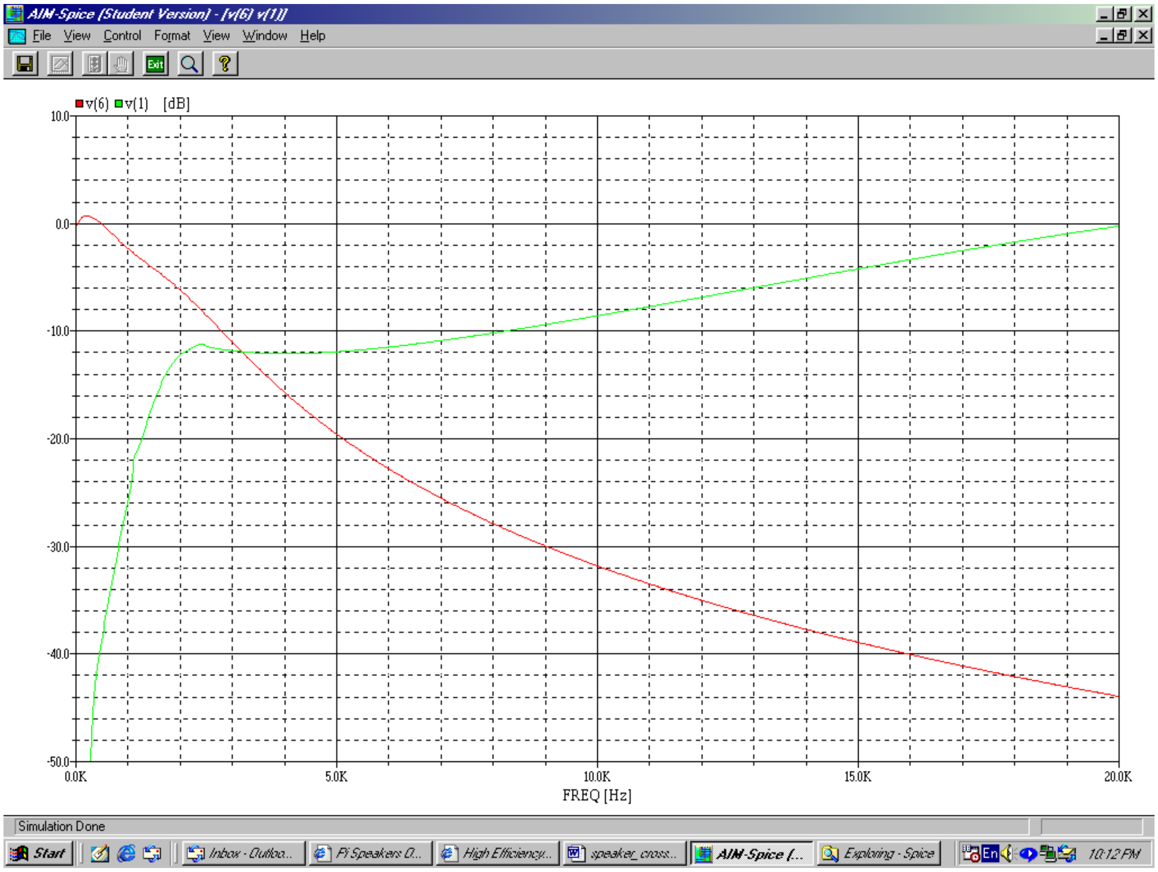
**Alpha 12 and PSD2002 with tweeter compensation network**



This is the response of the crossover – second order for the woofer and third order for the tweeter – and a compensation circuit for the tweeter. The compensation circuit is formed using a 25 Ω R1 resistor and 0.47µF C1 capacitor, and a 16 Ω R2 capacitor.

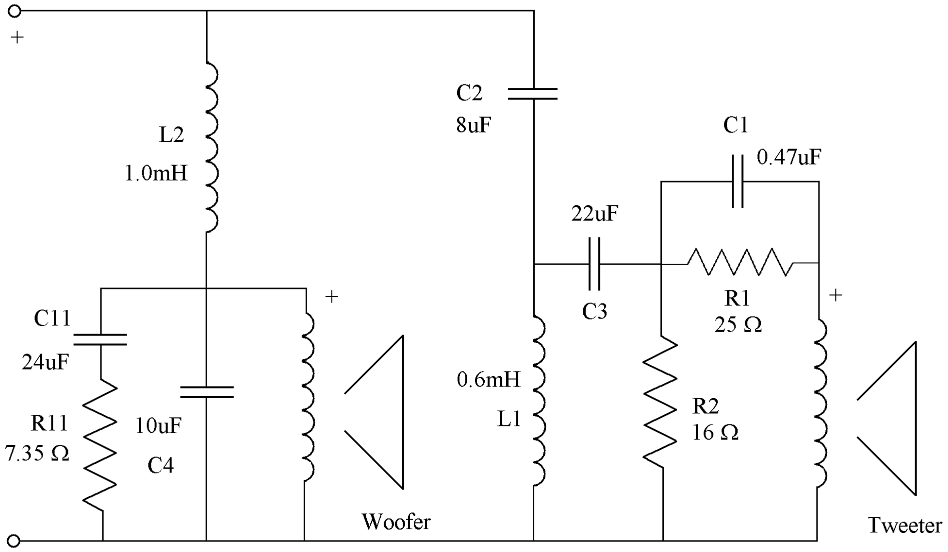
Notice that now we do not have a dip in tweeter response corresponding to the woofer peak. Damping from the tweeter's compensation circuit has successfully prevented its peaking and has also decoupled it from reactive interaction with the woofer circuit.

Let's examine the system using an RC damper for the woofer, to remove woofer peaking in the crossover region. Optimal compensation is found using a 7.35 Ω resistor and a 24µF capacitor.

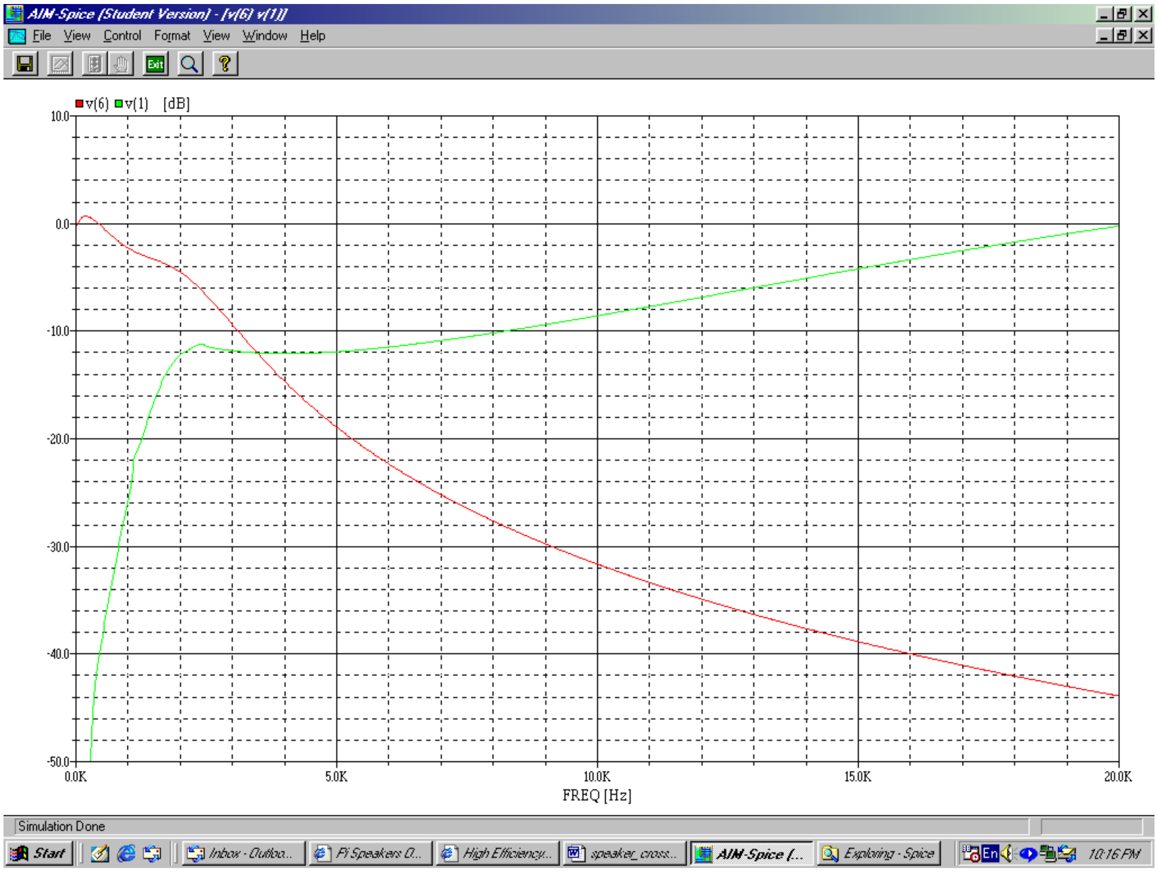


Simulation Done

**Response with HF compensation for tweeter and RC damper for woofer**

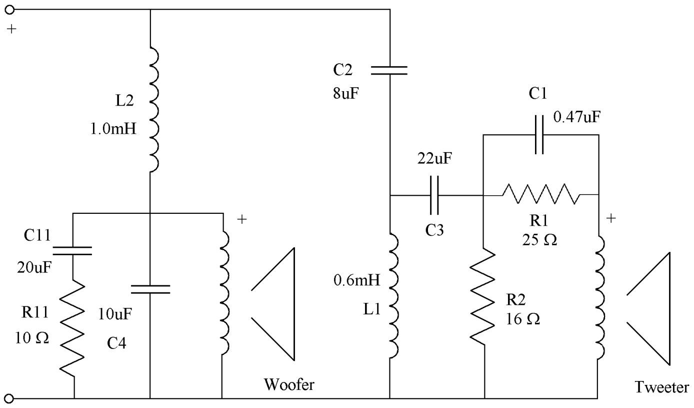


The response curve is perfect, both for the woofer and the tweeter. But the values chosen for the resistor and capacitor are difficult values to obtain. So let's analyze the circuit using component values that are more common.

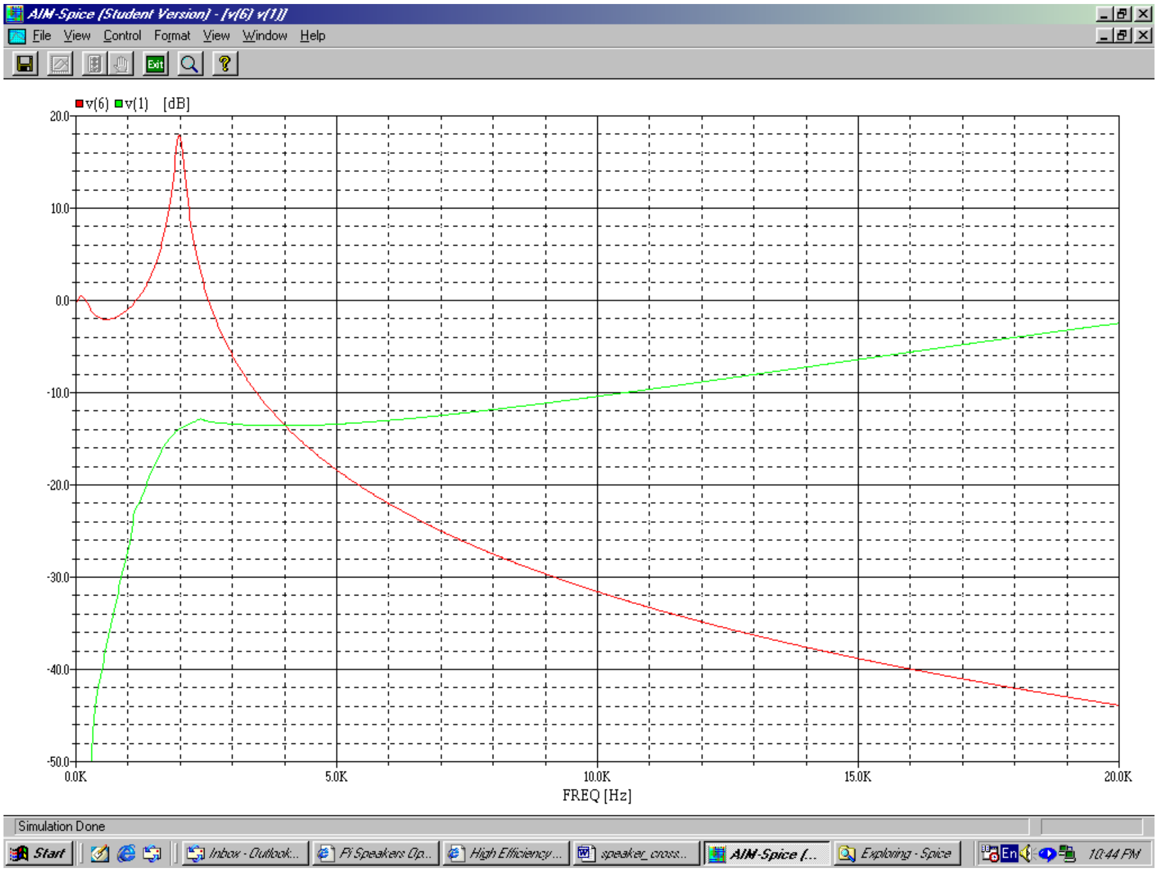


**Response using common values of R and C for RC damper**

This is the response curve of the system when the woofer's RC damper values are 10 Ω and 20µF. The response curve is only slightly different, and is perfectly acceptable. This shows that values between 7.35 Ω and 10 Ω and between 20µF and 24µF provide excellent RC dampers for this woofer.

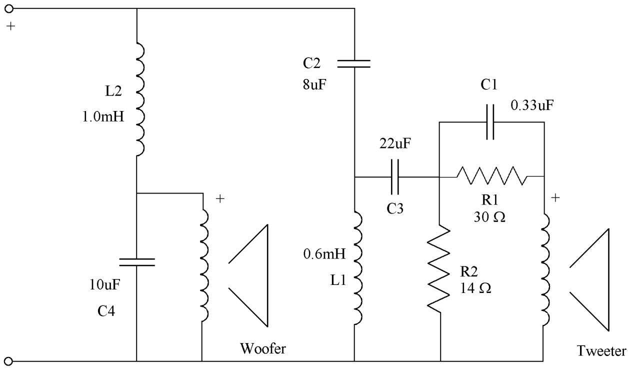


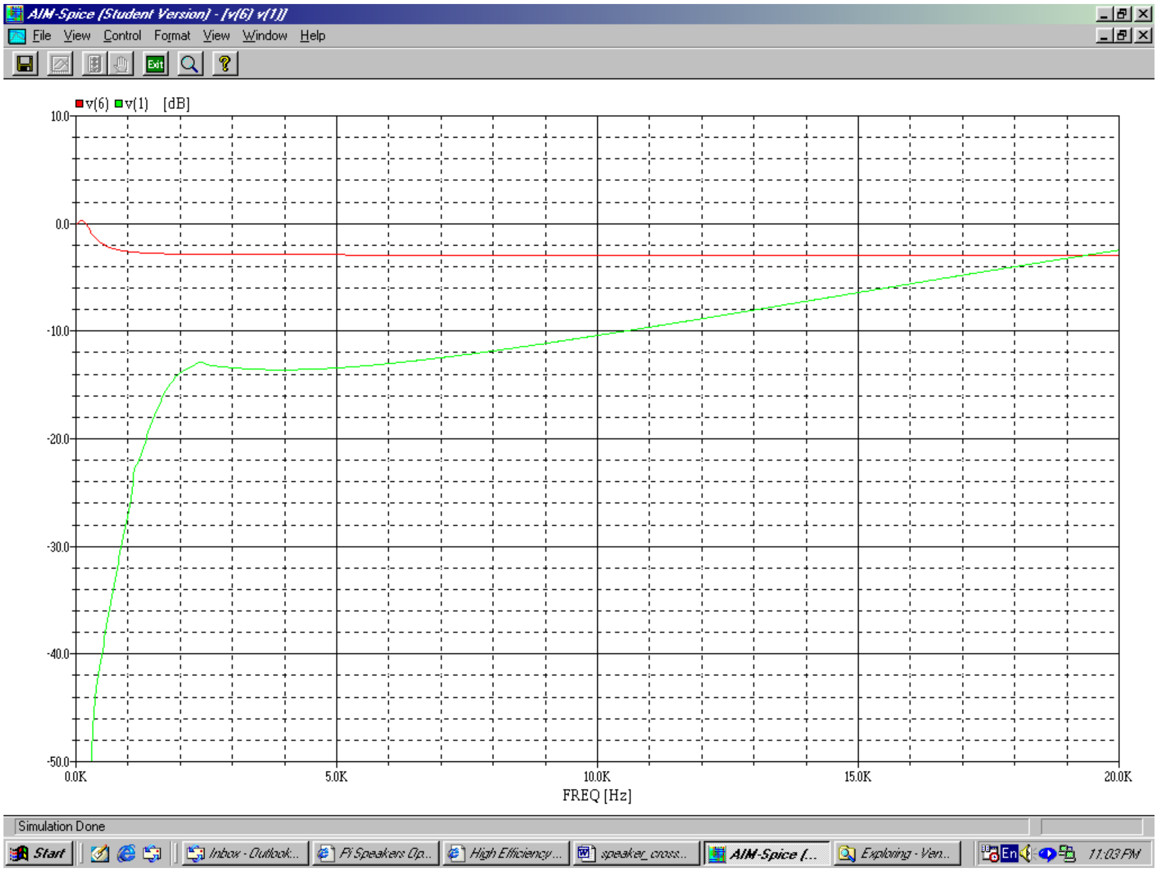
Let’s try this type of network on a woofer having a voice coil with high inductive reactance. The JBL 2226 is used with the Eminence PSD2002, and in this application, the compensation network is configured for 14dB attenuation. So the crossover is now configured to use a 14dB compensation network comprised of 30 Ω R1, 0.33µF C1 and 14 Ω R2. The woofer’s RC damper is removed for this demonstration.



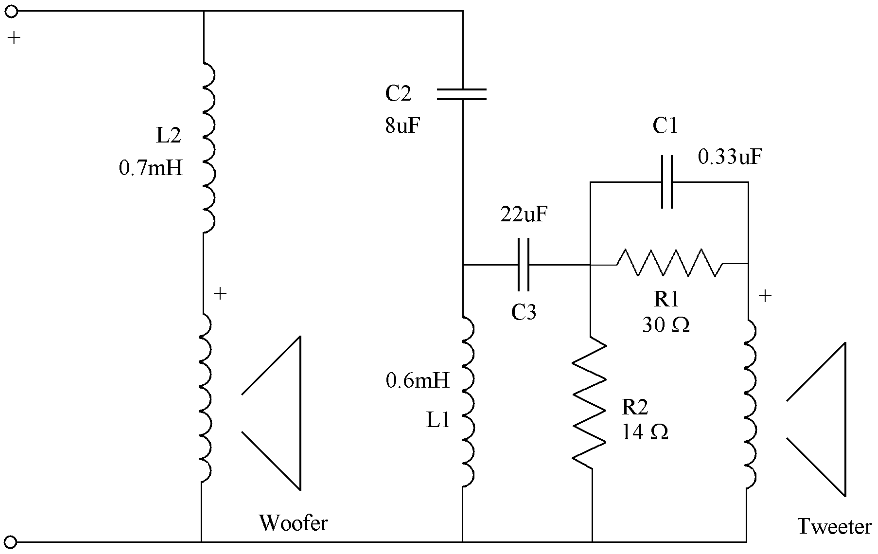
**JBL 2226 and PSD2002 with second order woofer network**

As you can see, woofer peaking with a standard second order network is unacceptably high at almost 20dB. This system will need to have an RC damper installed or it will need to be run as a “Pseudo First-Order” like was described on page 46. But since the woofer is a 600-watt component, the fixed resistor for an RC damper will also need to handle several hundred watts. This alone, makes an alternate option attractive. So let’s examine the “Pseudo First-Order” approach for this system.





**JBL 2226 and PSD2002 with “Pseudo First-Order” woofer circuit**



In this case, the woofer rolls off to a maximum of 3dB attenuation at cutoff, but does not ever exceed 3dB.  If a woofer has excessive HF cone breakup or does not roll off naturally around the desired cutoff frequency, this kind of simple network will not reduce HF enough and might not sound very good.  But if the cone flex resonance is mechanically damped and well behaved, this configuration sounds very nice.

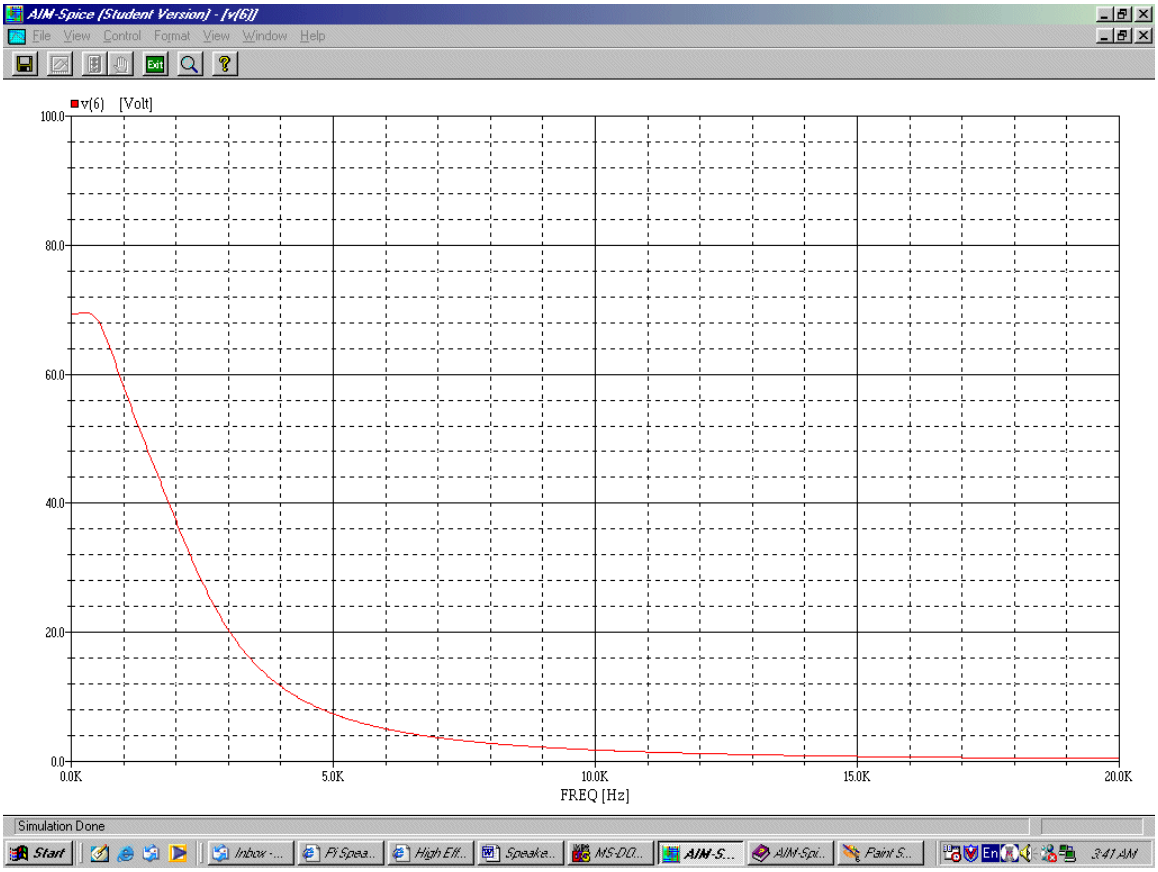
A conclusion is evident:  RC dampers or “Zobels” are *only* required on woofer circuits that use networks *greater* than first order.  They are *not required* on woofers using “Pseudo First-Order” filters, and in fact, this is what defines them as such. Also, Zobels are rarely required on tweeters.

For higher order networks, a working simplification is that woofer compensation RC damper circuits – Zobels - may be omitted if voice coil inductance is less than crossover inductance.

## Component Rating – Power and Voltage

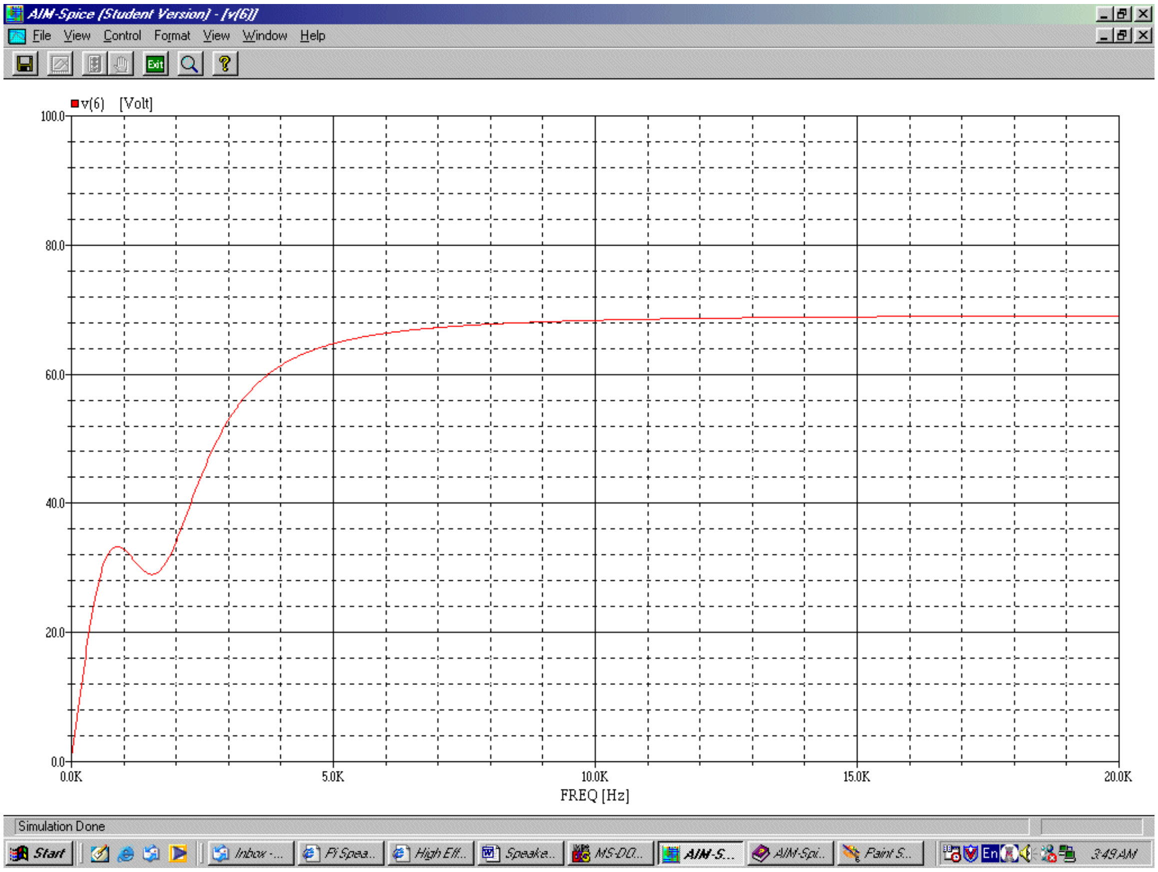
Each of the components in the crossover filters is exposed to the same signal, but each divides the signal proportionally as a function of frequency. So to find the voltage rating required of capacitors, and the power or current rating required of resistors and coils is a non-trivial task. Below, we will examine each component and subject it to a swept sine wave of 70 volts peak, which is 50 volts RMS and would generate 300 watts across an 8-ohm resistive load.

The following charts all use the 1K6a010dB and the Zobel network used in the Theater Series four π Speaker. The data shown is accurate for this particular network, but will be slightly shifted for other networks because they have slightly different components. However, the general trends shown will be the same.



**Voltage across capacitor C4 and Woofer**

The voltage across these components, and the power dissipated by them, is somewhat easy to imagine. Under the woofer's crossover frequency, the voltage is approximately equal to the full 70V peak, or 50VRMS. Naturally, the woofer receives the full 300 watts RMS under the crossover frequency, and signal content is rapidly attenuated as we approach the crossover frequency.



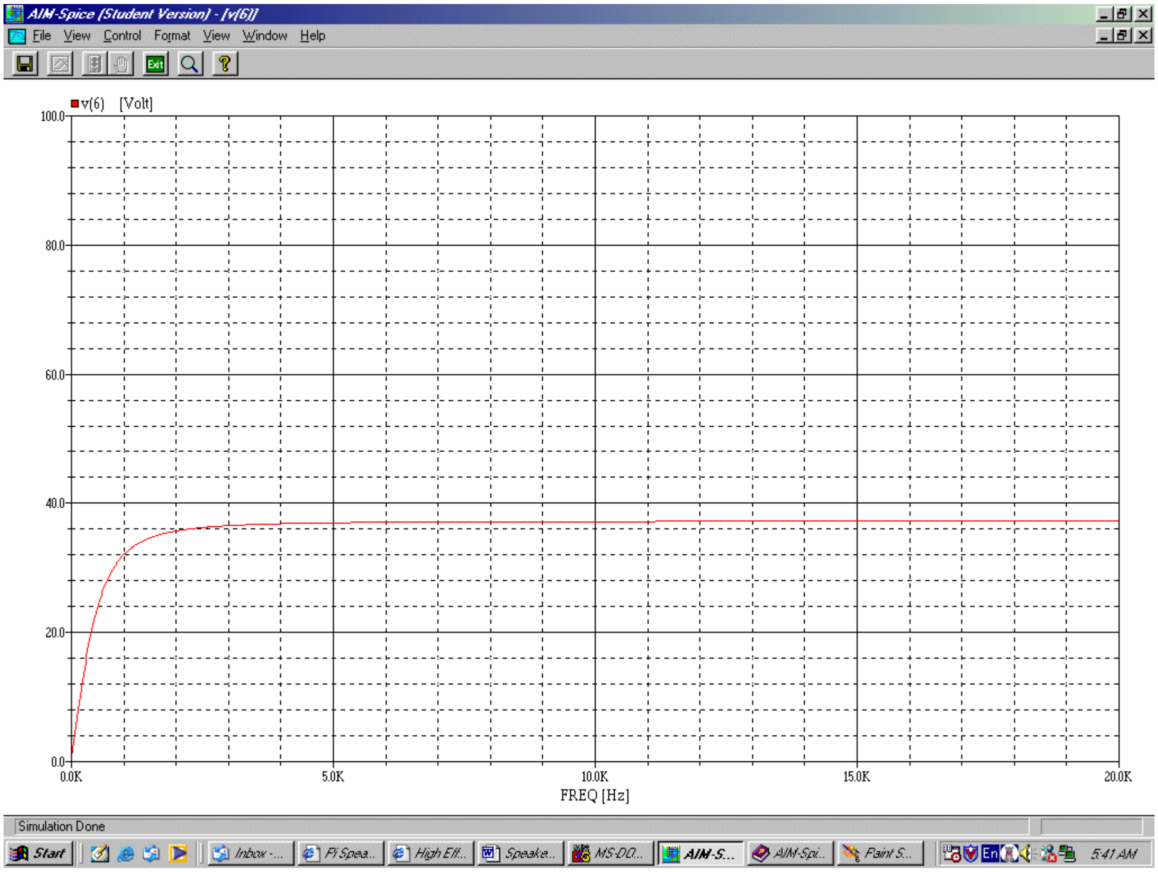
**Voltage across inductor L2**

The voltage across the coil in the woofer circuit is also easy to guess, having low voltage across the device at low frequencies where energy readily passes, and full amplifier voltage across the device at higher frequencies. To calculate current and power, we must employ our inductive reactance formula:

$X_L = 2\pi FL$

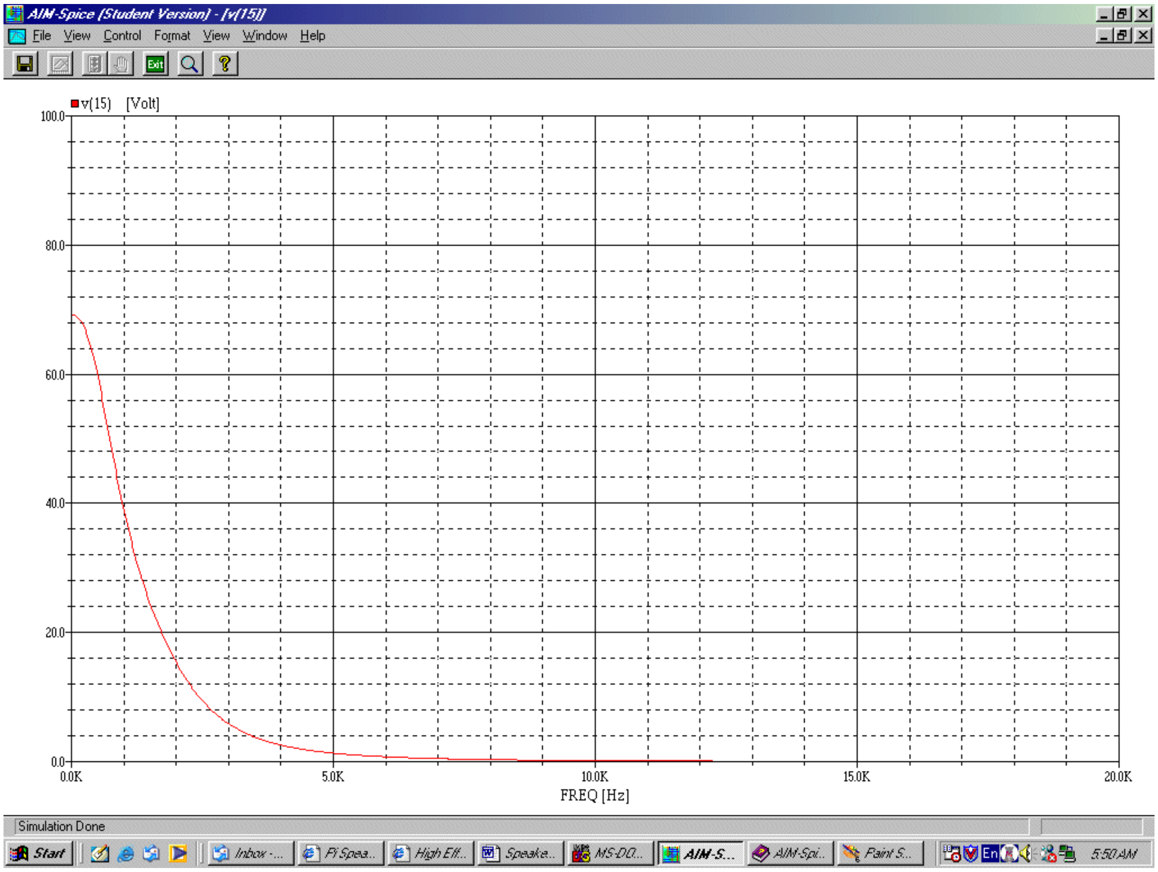
And since the most interesting features are the voltage peak around 800Hz and the current peak at the crossover frequency, 1600Hz, we should calculate power at these frequencies.

At 800Hz, the inductive reactance formula equates to $X_L = 2\pi(800)(1x10^{-3})$ or 5 Ω. At 1600Hz, inductive reactance is 10 Ω. Since peak voltage at 800Hz is 33V, peak current is 6.6A, making peak power 217 watts. RMS voltage is 23V, current is 4.6A and power is then 108 watts. At 1600Hz, peak voltage is 28V, current is 2.8A and power is 78.4 watts. Clearly then, the maximum is 4.6A (RMS), which is a little over 100 watts RMS.



**Voltage across inductor L2, if configured as Pseudo First-Order**

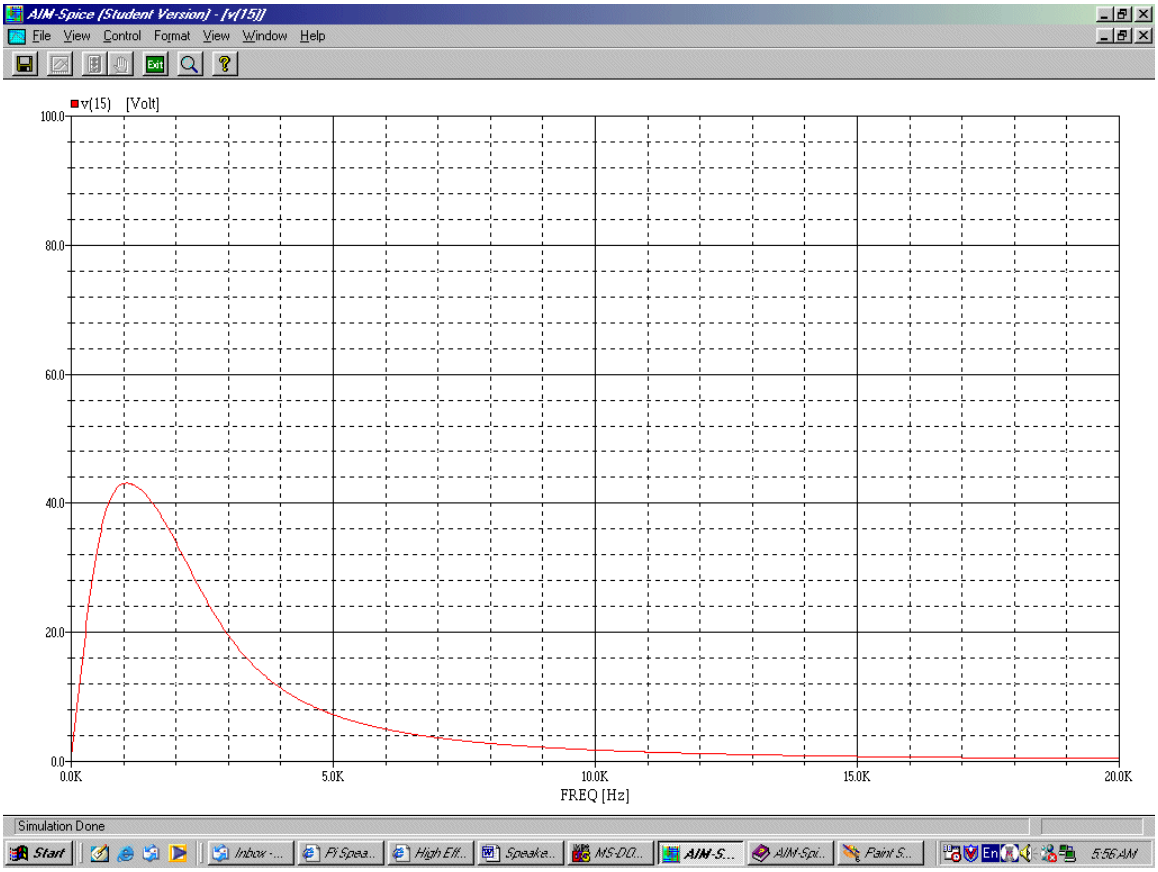
If the Delta 15 woofer in the Theater Series four π Speaker were to use a Pseudo First-Order filter, the curve above would represent the voltage across coil L2. In this configuration, C4, C5 and R3 are removed from the circuit. As you can see the inductor acts as little more than a frequency-constant voltage divider above 1kHz.



Simulation Done

Voltage across woofer damper C5 (Zobel)

The voltage across capacitor C5 is similar to the voltage across C4. Its maximum value is at DC and it falls rapidly. For a 300 watt RMS loudspeaker, the peak value is 70 volts.

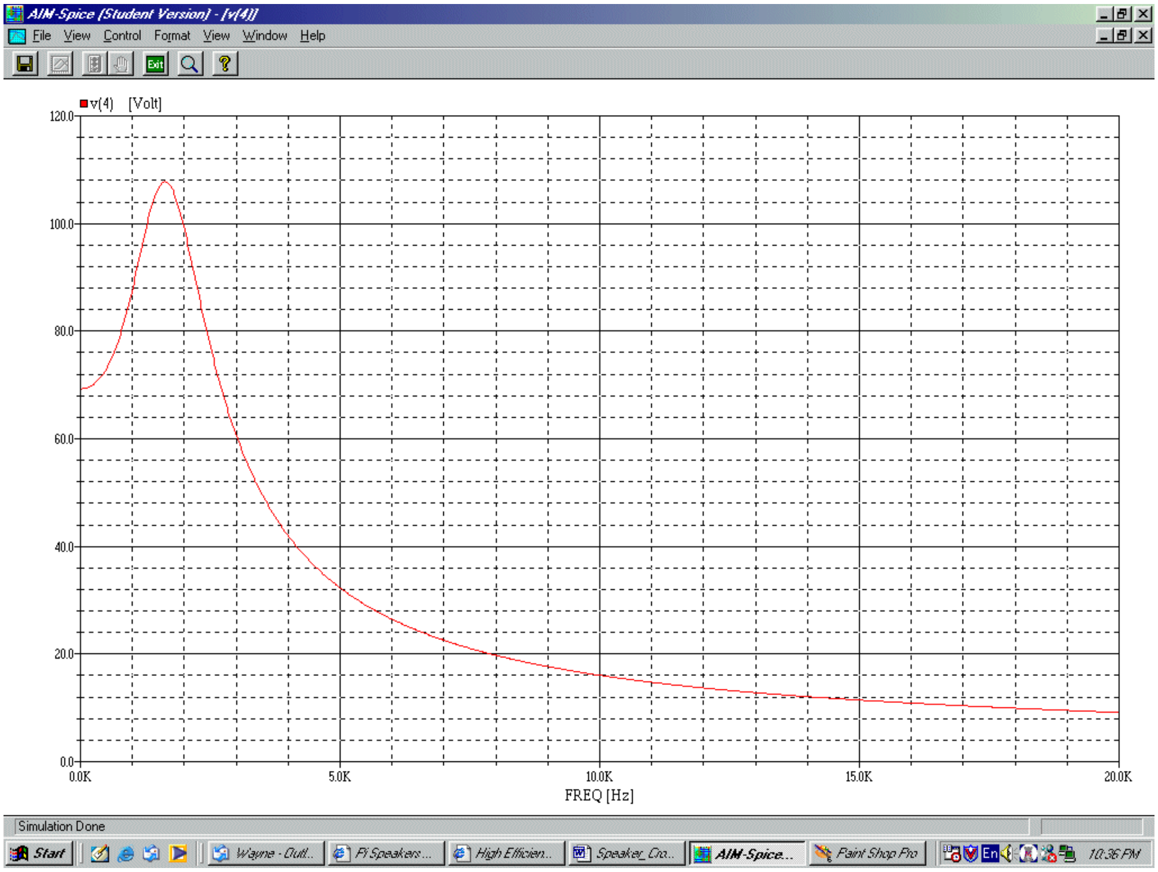


**Voltage across woofer damper R3 (Zobel)**

The graph above shows voltage across the Zobel resistor with respect to frequency. As you can see, maximum voltage is in the octave below crossover, and it peaks around 44 volts, which is 31 volts RMS. To solve for power, use the following formula:

$P = E^2/Z$

Therefore, peak power is $44^2/8$ or 242 watts and RMS power is $31^2/8$ or 121 watts.



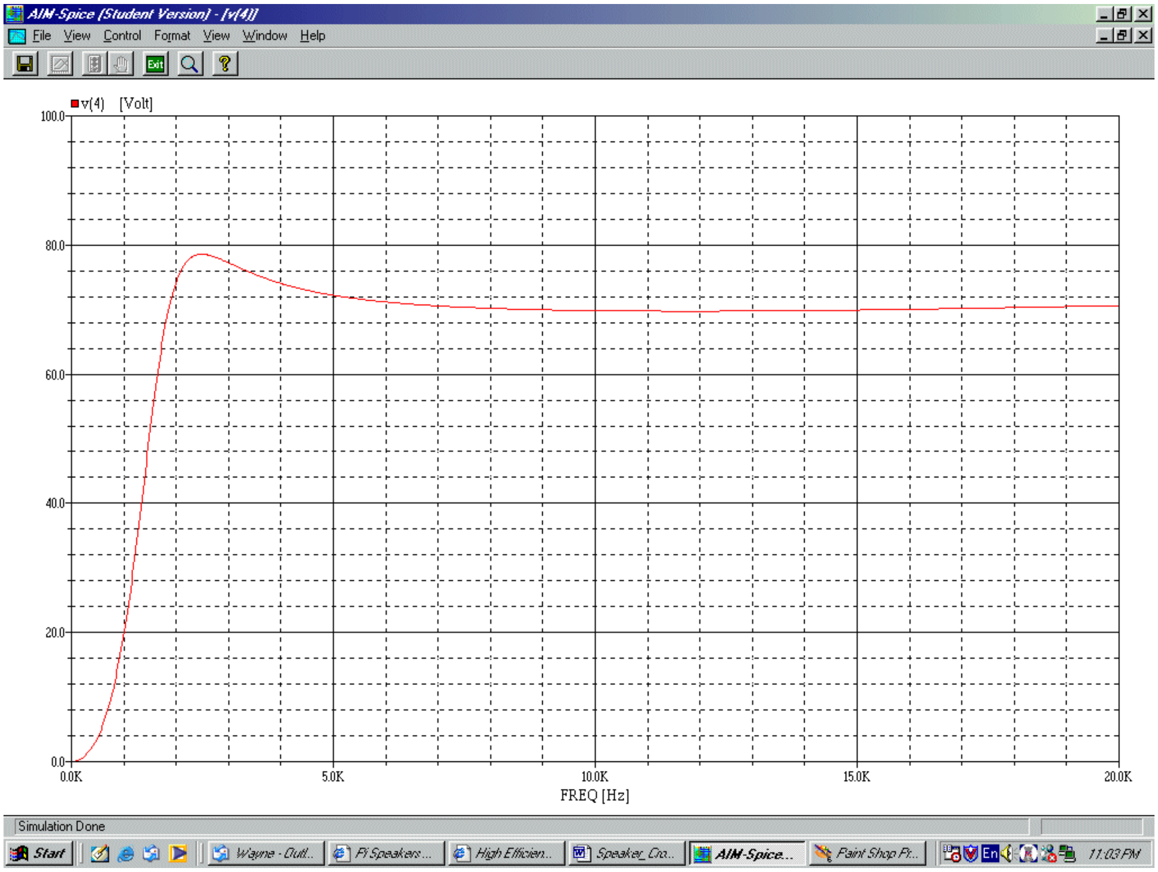
Simulation Done

**Voltage across capacitor C2**

The voltage across the initial capacitor in the tweeter's third order filter shows a significant amount of peaking. This is caused largely by the interaction with inductor L1 and the fact that there is relatively high load impedance so this part of the filter remains underdamped. This capacitor receives over 100 volts at its peak, which is about 75 volts RMS.

I suggest using a capacitor rated greater than 100 volts in this circuit position if used in a 300-watt loudspeaker system. Capacitors rated 250V or 400V are preferred, and offer further protection against increased peaking in the event that the damping resistor R2 fails. *If any of the compensation components or the tweeter fails, then damping of the filters is significantly reduced and peaking of this device will increase.*

You may at first think that there is some error, in that more voltage is present across this device than has been put into the system. And in fact, this is exactly what is happening. Energy between the inductance and capacitance in a resonator is alternately charged and then dumped back and forth into each other, in a manner that causes the system to appear to have more energy than was put into the system. This is the nature of LC circuits at resonance, and in fact, of any system in resonance.



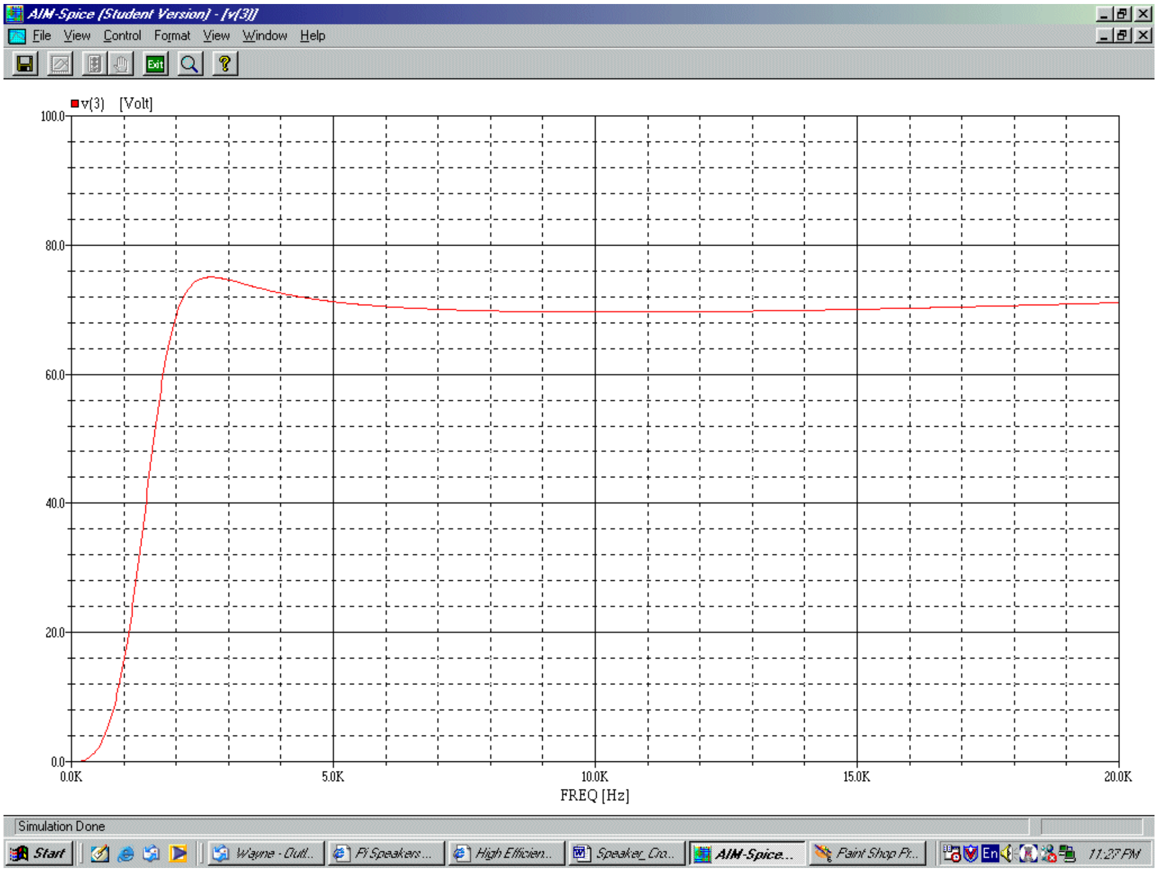
**Voltage across inductor L1**

The signal across L1 is as a person might expect, having no content below the crossover frequency and an almost perfectly linear power distribution above the crossover point. There is a slight peak at crossover, which is caused by the Q of the filter and set primarily by the load resistance R2 in relation to the reactive components L1, C2 and C3. The slight rise in the higher frequencies is caused by HF compensation components R1 and C1.

Since inductive reactance increases proportional to frequency, current and power dissipated is reduced as frequency goes up. The highest current and power is within the peaking band, which is in the octave above crossover. Voltage at 2.4kHz reaches its highest point, nearly 80 volts peak or 55 volts RMS. Inductive reactance at this frequency is 9 Ω, which then translates to 6.1A and 336 watts RMS.

Like the voltage across C2 at resonance, more power is seemingly dissipated in this single coil than has been put into the system. And again, this is exactly what is happening. Instantaneous power is more than double our input power, peaking at 672 watts.

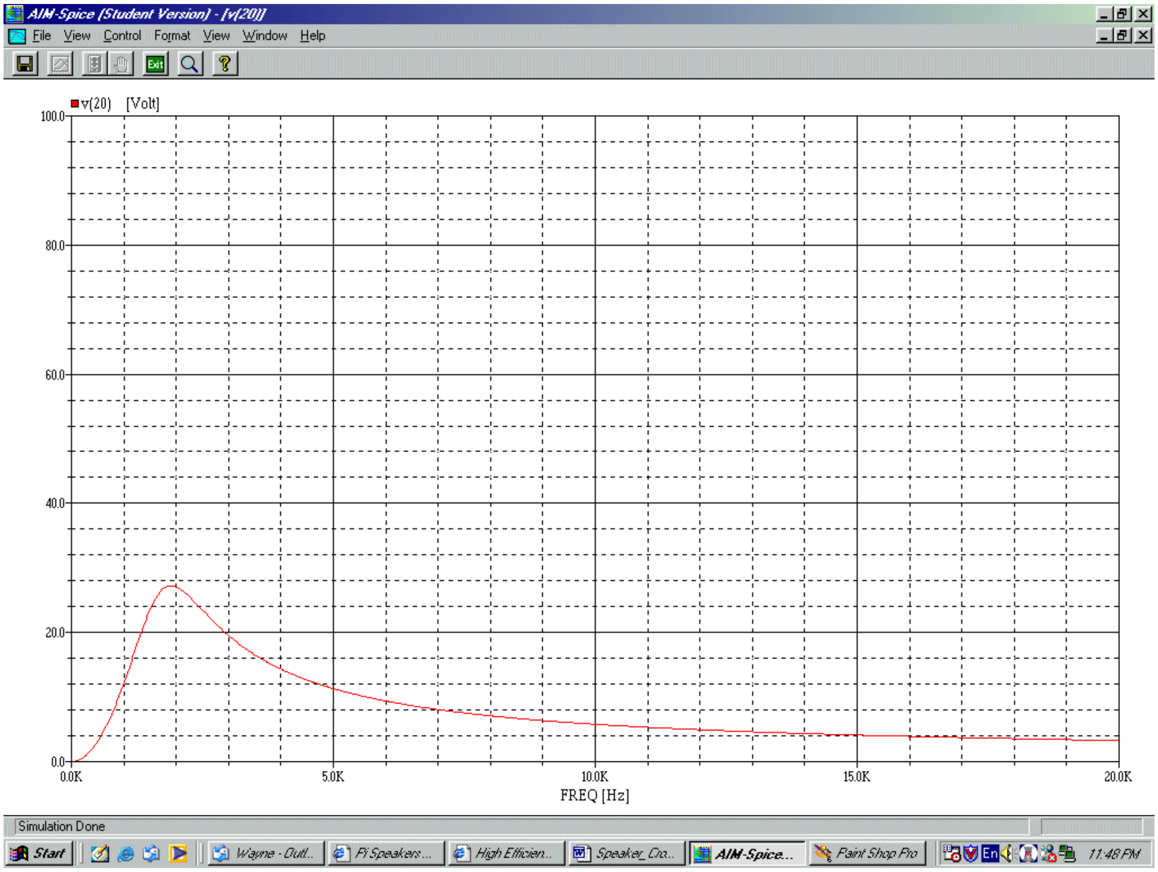
So we see that in the octave above crossover, a significant amount of current flows through this component.



Voltage across resistor R2 (tweeter compensation)

The voltage across the tweeter's compensation load resistor R2 is almost identical to the signal across the crossover filter's shunt inductor L1. This is easy to understand, since they are only separated by capacitor C3. But since resistor's impedance is fixed and does not increase as a function of frequency, the current and power dissipated by this device will be nearly the same for all frequencies above the crossover frequency. There is a small peak in the octave above crossover because the filter is slightly underdamped.

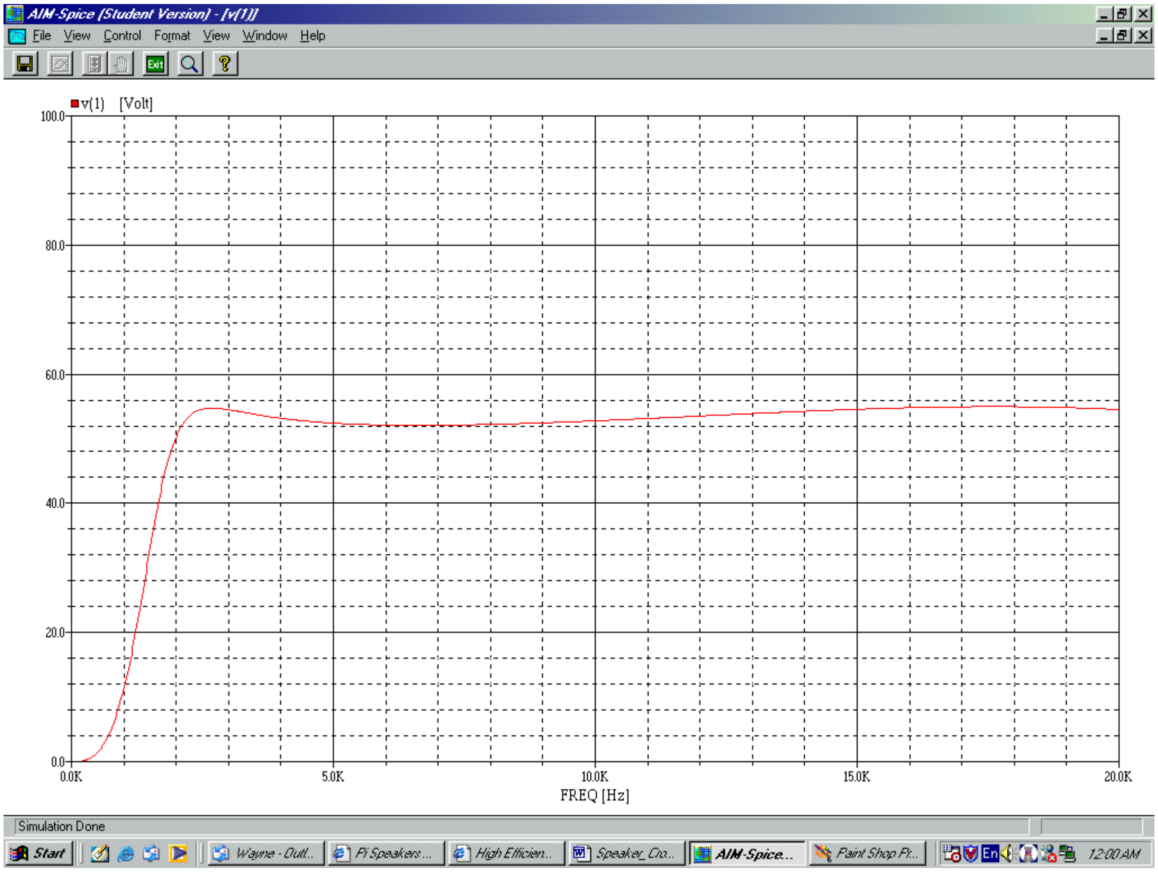
Maximum voltage is 75V peak or 53VRMS at 2.4kHz. This translates to 3.3 amps or 175 WRMS.



Simulation Done

**Voltage across capacitor C3**

Based on the power transfer curves of L1 and R2, the small signal across capacitor C3 is as expected. Maximum voltage is less than 30 volts peak, which isn't even half the voltage presented to the system at this frequency. The only place where energy rises across this component is in the octave above crossover, where filter peaking occurs.



Simulation Done

**Voltage across capacitor C1 and resistor R1 (tweeter compensation)**

Voltage across these two components is a fairly consistent 55 volts at all frequencies above crossover. At peaking, it reaches a high of around 58 volts, and over the first few octaves it dips to around 52 volts. Peak voltage or 58 volts is 41VRWM and current through resistor R1 is then 2.56A, or 105 watts RMS.

## Final comments about power and voltage ratings

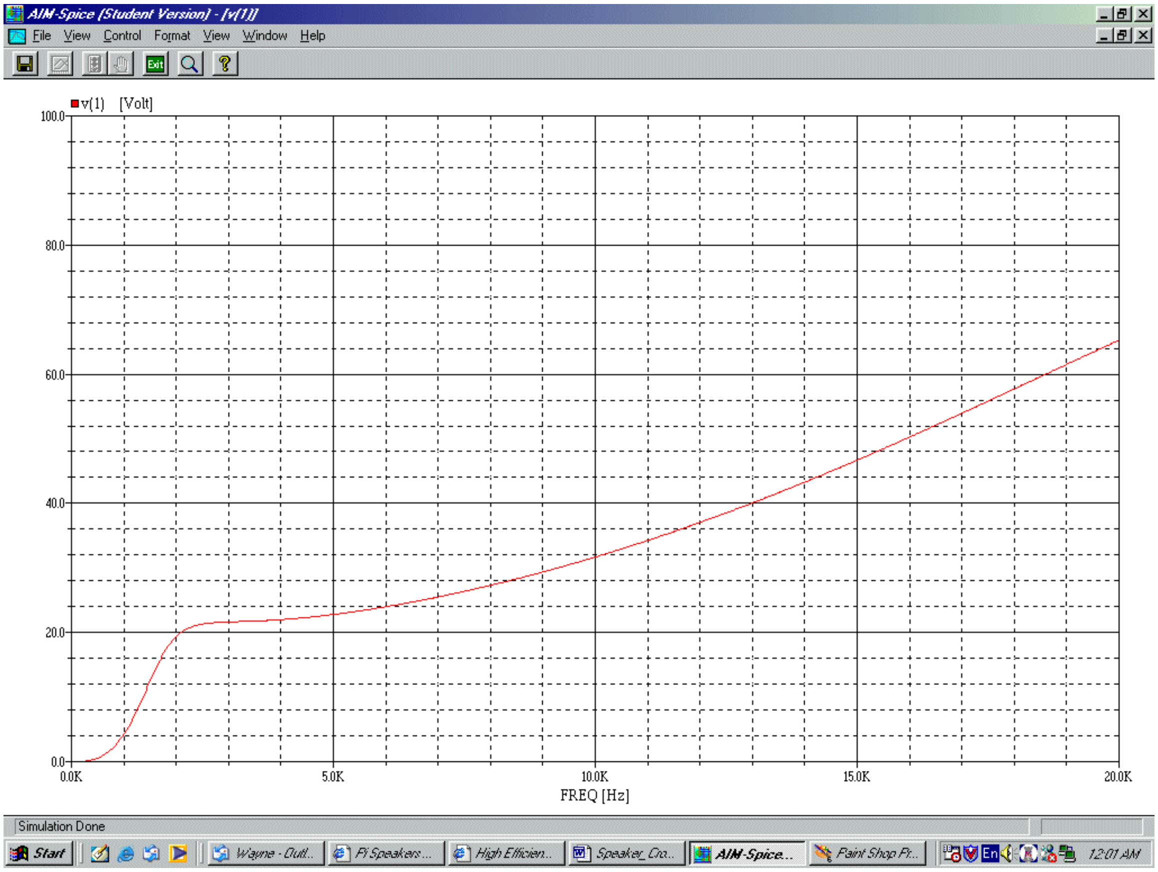
Notice that both capacitors C1 and C3 can be safely implemented with 100-volt components and resistors R1 and R2 should each be resistors rated at least 100 watts. However, signal distributions are normally weighted heavily in favor of the midbass and lower midrange band, with energies normally much lower in the upper midrange and treble. Because of this, and the economics and availability of high power resistors as opposed to high voltage capacitors, an adequate compromise may be made.

Results have been found to be good using resistors rated at 25% to 50% of the power levels described for the tweeter circuit. When doing this, two things should be understood:

1. Normal signal distribution is such that these levels are adequate, however, a sine wave of full power sent solely to the tweeter subsystem may cause de-rated resistors to fail, particularly if sent in the peaking frequencies between 1.6kHz and 3.2kHz.

2. If either resistor R1 or R2 fails, filter peaking between 1.6kHz and 3.2kHz will be much higher, placing higher voltage on the capacitors C2 and C3 and causing higher current to flow through L1. So if resistors R1 and R2 are de-rated, then capacitors C2 and C3 and inductor L1 should be pro-rated to compensate. This is a fail-over design solution, and is suggested to keep from having one failure escalate into many, and possibly damaging the most expensive component in the system, which is the tweeter motor itself.

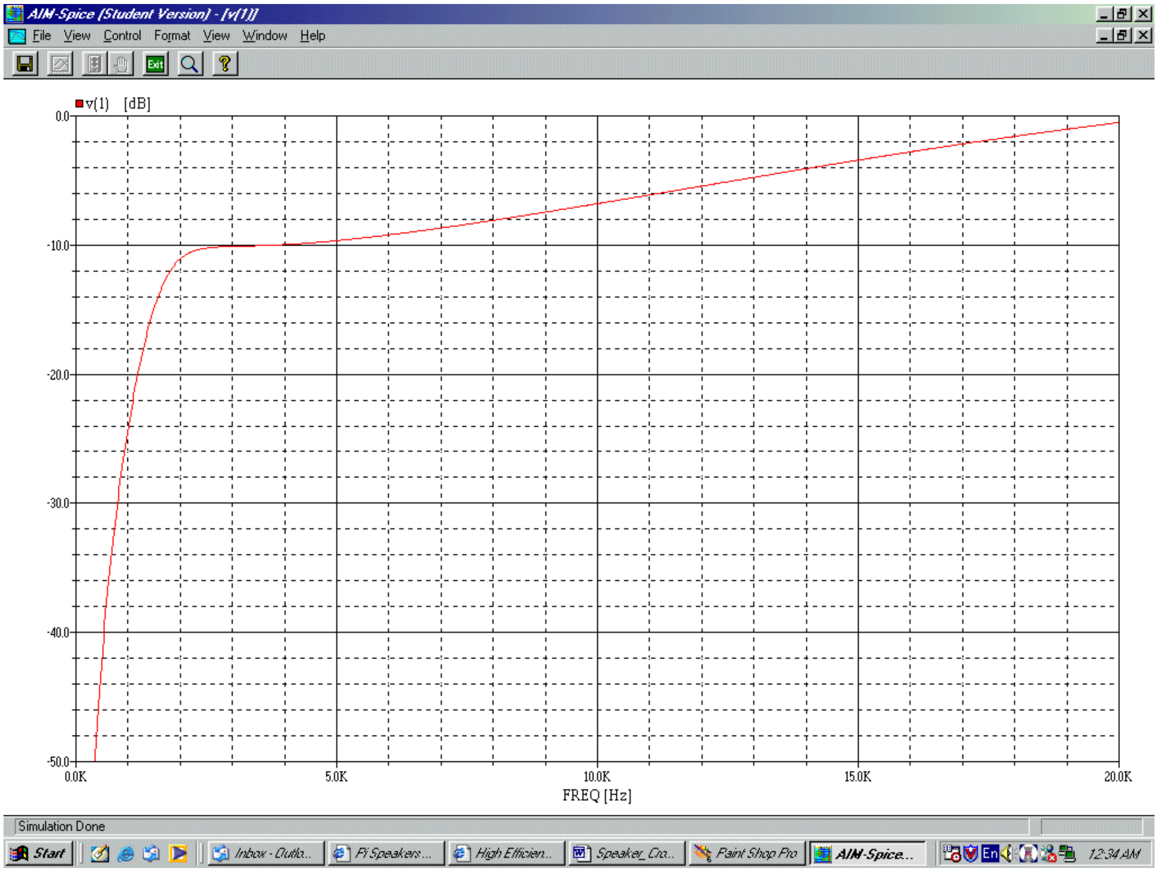
This rating mechanism is a design choice based primarily on economics and the availability of components. It has been found to be more than adequate.



Simulation Done

**Voltage across tweeter**

The signal output from the tweeter circuit filters provides the response curve shown above, as expressed as a swept voltage. It may appear to have more amplitude than you are used to seeing, since it is expressed as a voltage graph rather than in decibels.



Simulation Done

**Signal across tweeter, expressed in terms of decibels**

Expressing the tweeter signal in terms of decibels puts it back into a format that most people are familiar with. This is the same curve as shown on the preceding page, but shown having a decibel scale rather than as a voltage.

Having examined all parts of the electrical filters used in loudspeakers, one can make much more informed decisions about what is required, and what is not. The import of each component, when shown by quantified example, makes it much easier to assess the full value of the crossover filter in the loudspeaker system.

It is clear that it is not enough to consider only the acoustic response of the speaker motor and its cabinet, because the electrical components in the crossover provide a filter function. And it is also clear that one cannot simply dismiss a single component as having "less in the signal path" when it may impart significant peaking to the system that could be removed by a more appropriate network solution.