Chapter 13. System Optimization

Background

Crossover optimization is considered to be the final stage of fine tuning the design. After the individual channels have been designed and optimized, The optimizer tool should be employed to determine if any further improvement in the frequency response of the system can be obtained. There are a number of factors which must be considered when determining the crossover cut-off frequencies and the speed of the roll-off. Some of the loudspeaker drivers on the market must be used with crossovers having a high roll-off speed because of their power handling characteristics. Should this be the case some caution is advised when using the optimizer tool. The algorithm employed within the module is not bound by the power restrictions of the driver. The prevailing factor assumed by the algorithm is the minimization of the error between the target and system frequency response.

Typically, you would use System Optimizer to reduce the negative effects of different drivers' Acoustic Centre distances to the summation point (microphone).

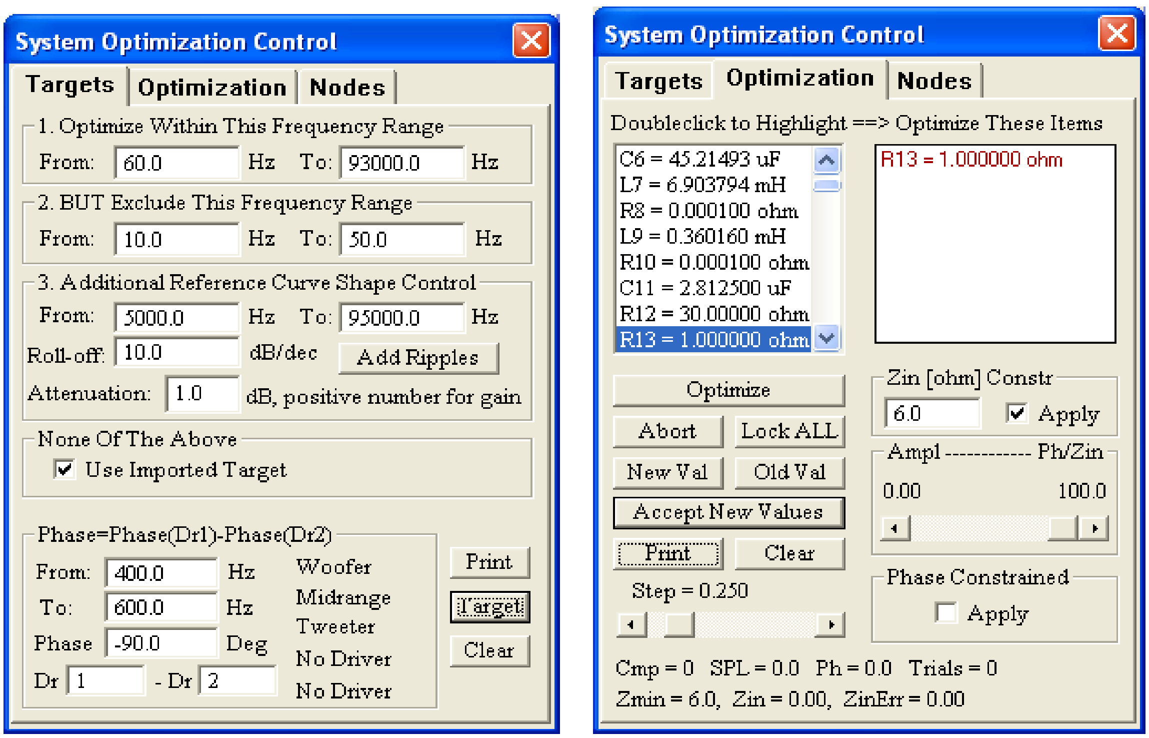


Figure 13.1.Optimization Control Dialogue Tabs

System Optimization Control – Targets Tab

1. **"Optimize Within This Frequency Range"** - two editable fields to accomplish just that. Enter frequencies in Hz.
2. **"BUT Exclude This Frequency Range"** – again, two editable fields to accomplish just that. Enter frequencies in Hz.
3. **"Additional Reference Curve Shape Control**" - group has four editable fields. The **"From"** field selects the frequency (in Hz) from which the response is to roll-off. . The **"To"** field selects the frequency (in Hz) at which the response is to flatten again The third field - **"Roll-off**"- is used to enter the required tilt in dB/decade. Usually, it is a small amount: 1-3dB/decade.
4. The **"Attenuation" parameter indicates, how much we would have to shift the 90dB reference line to match the system efficiency. For example: system efficiency is 86dB, enter "Attenuation" as –4.**

5. It is recommended, to use **“Target”** button on the dialogue box to review system target reference line before commencing optimization process. The “**Target**” button allows you to plot the reference curve on the screen without commencing optimization and is particularly useful when using “tilted” mode.
6. **“Add Ripples”** – this button closes the “Optimization Control” box and opens another box to enable you to add 3 ripples.
7. **“Phase=Phase(Dr1)-Phase(Dr2) Group”**
   “From” – enter required starting frequency of the band.
   “To” – enter required end frequency of the band.
   Phase response is typically changing much more rapidly with frequency, than the amplitude response. Therefore, the selected frequency range should be significantly narrower than typical SPL optimization frequency range.
   “Phase” – enter desired reference phase value.
   “Driver #” – enter the first driver number as displayed in “Drivers Used” list.
   “Driver #” – enter the second driver number as displayed in “Drivers Used” list.
   Phase response to be optimized it the phase difference between those two nominated drivers.
8. **"Clear"** button will erase the plotting area.
9. **“Use Imported Target”** – Check this box if you need to use imported target curve**.**

System Optimization Control – Optimization Tab

1. **“Lock All”** – Button to lock all values from optimization.
2. **"Clear"** button will erase the plotting area.
3. **"Abort"** button will cause the program to exit from the optimization routine.
4. **When the "New Values"** button is clicked upon, the original component values are substituted for the newly optimized.
5. When you click on the **“Old Values”** button, the process is reversed. Once again, plotting the reference curve and the driver's frequency response leads to determination of the optimization boundaries.
6. **“Accept New Values”** – press this button to accept newly optimized component values
7. Click on **"Optimize"** button to commence the optimization process or to edit the target response parameters.
10. **Zin [ohm] Constr - “Apply”**: - editable data field to enter the lowest acceptable input impedance your amplifier can tolerate. **MUST be greater than 0.1ohm**
11. **Zin [ohm] Constr - “Apply”**: checkbox to enable/disable Zin restriction.
12. **Phase Constrained - “Apply”** – checkbox to enable/disable Phase restriction.
13. **“Amplitude ----- Ph/Zin Group”** - use this slider to apportion mutual importance level to amplitude and phase OR amplitude and impedance.
14. **“Step” + slider** – Selectable values are from 1 – 200%. This parameter sets the initial step for adjusting component values. Default value is set to 25%, and it is not recommended to change it unless optimization results can not be accomplished. Setting step too high may lead to “runaway” problems.

Please note, that SPL optimization is achieved by un-checking **Zin [ohm] Constr - “Apply”** checkbox, and un-checking **Phase Constrained - “Apply”** checkbox.

Nodes Tab – the same as previously described for Cad system.

Researchers recommend, that only one channel should be optimized at a time. Hence, the optimizer tool allows the user to select woofer, upper bass, midrange, tweeter or super tweeter channels, together with the frequency range of the optimization. The frequency range must match the selected driver. This program has been developed for use with reactances including their "real life" losses. Thus inductors are modeled with their associated resistances and the complete model is the used by the optimization modules. As a result of this, the optimization algorithm may recommend increasing the inductor’s resistance, should you decide not to LOCK it. Please remember, that it will have some effect on the total Q-factor of the driver connected to this crossover branch. It is also recommended to experiment with inductors having lower resistance losses, if only to avoid power loss.

Setting-up For System Optimization

We are now going to perform possibly the simplest optimization on a 3-way system. A step-by-step approach will be presented, that can be subsequently expanded for more complicated optimization cases.

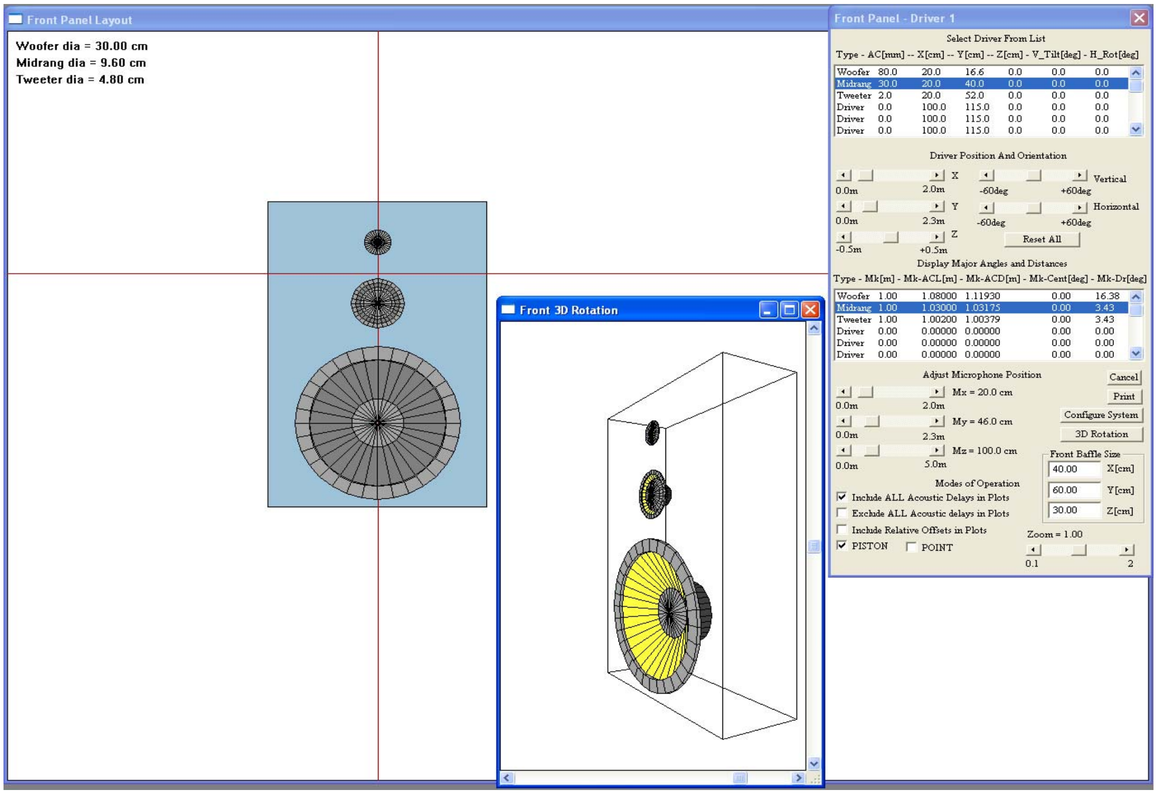


Figure 13.2 Test system set-up for optimization.

Loudspeakers that we decide to use in this example have the following characteristics:

1. Woofer: Efficiency = 91.0dB, acoustic offset = 80.0mm
2. Midrange: Efficiency = 92.5dB, acoustic offset = 30.0mm, L-Pad = -1.5dB
3. Tweeter: Efficiency = 91.0dB, acoustic offset = 2.0mm.

It is clear, that we are aiming at **system efficiency of 91.00 dB**. Additionally, only the midrange-tweeter crossover point will be optimized, however, you may apply the same principles to any other driver optimization. Finally, for the purpose of illustrating the optimization process, we are interested in **maximally flat frequency response above 1.5kHz**. Topology of our design is depicted on Figure 13.2. Here we have the tweeter driver mounted on the top (Y=100.0cm) followed by midrange driver (Y=130.0cm) and the woofer is mounted at the bottom of the baffle (Y=170.0cm). As you can see, this would be a typical arrangement for a 3-way loudspeaker system. **Where do you place the microphone ?.** As we have decided to focus on optimization of the midrange-tweeter crossover section, therefore, we will place the test microphone right between those two drivers (Y=115.0cm). This will be confirmed by equal distances from both AC centers of drivers to the test microphone (1.04087m) and equal angles from both drivers to the test microphone (8.53deg) – see Figure 13.1. The selected microphone location is actually quite common location for the test microphone.

Right now, we have a situation, where the acoustic center of the midrange driver is further away from the test microphone by 28.0mm (30.0 – 2.0 = 28.0mm). We have two options to compensate for this: (1) introduce electronic delay – just as described in previous chapters, or (2) physically offset the tweeter by the 28.0mm to bring it "in-line" with the midrange acoustic center. In this example, we decided on the second option. **This final set-up is clearly depicted on Figure 13.2**.

Estimating the Required “Attenuation” Parameter and the Frequency Range

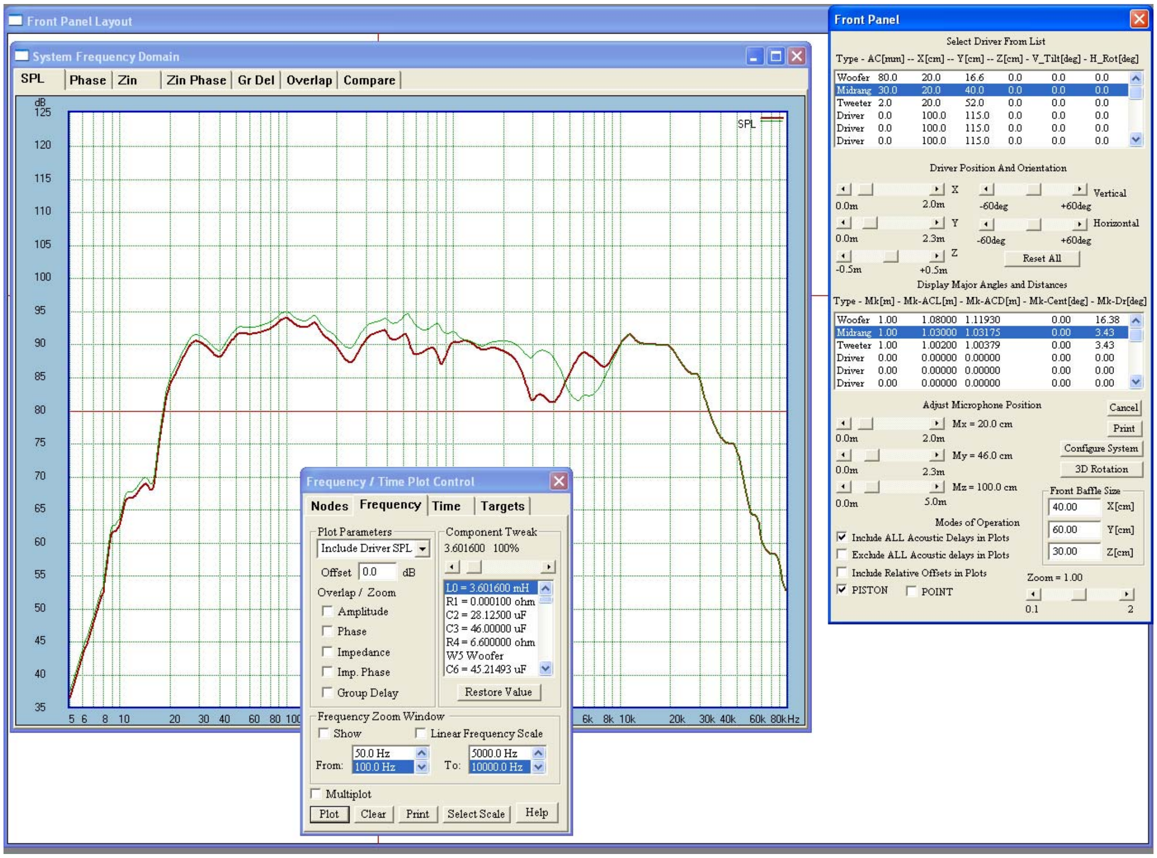


Figure 13.3 Lower plot (red) is about the “Include All Acoustic Delays” plot.

Assuming, that all your drivers were measured at 1.00 meter distance (not including acoustic offsets) we are now trying to estimate, **how much additional attenuation we have introduced by placing the test microphone marginally further away from midrange and tweeter**.

Let us focus on the frequency range of interest: 2kHz – 10kHz, which is where the intended optimization will take place. Make sure, the you set the check box at the bottom of the “Front Panel Layout” to “INCLUDE Acoustic Delay In Performance Plots” position, and plot the system frequency response.

Next, set the check box at the bottom of the “Front Panel Layout” to “EXCLUDE Acoustic Delay From Performance Plots” position, and re-plot the system frequency response on the same screen. In this example, it is not possible to estimate the drop in level. Obviously, the difference in SPL curve is noticeable, but this is due to adding/disregarding delays.

Therefore, the **system efficiency, as measured at our test microphone location will be 91.0dB.**

Now, the **“Attenuation” parameter indicates, how much we would have to shift the 90dB reference line to match the system efficiency** (as above, 91.0dB in this case). Therefore, the “Attenuation” parameter is **set to 1.0dB**.

Please note, that midrange crosses over to tweeter at 5kHz. Therefore, we set the optimization frequency range 1.5kHz to 20kHz – which is approximately 2 octave below and above the 5kHz cut-off.

Deciding Which Components to Optimize

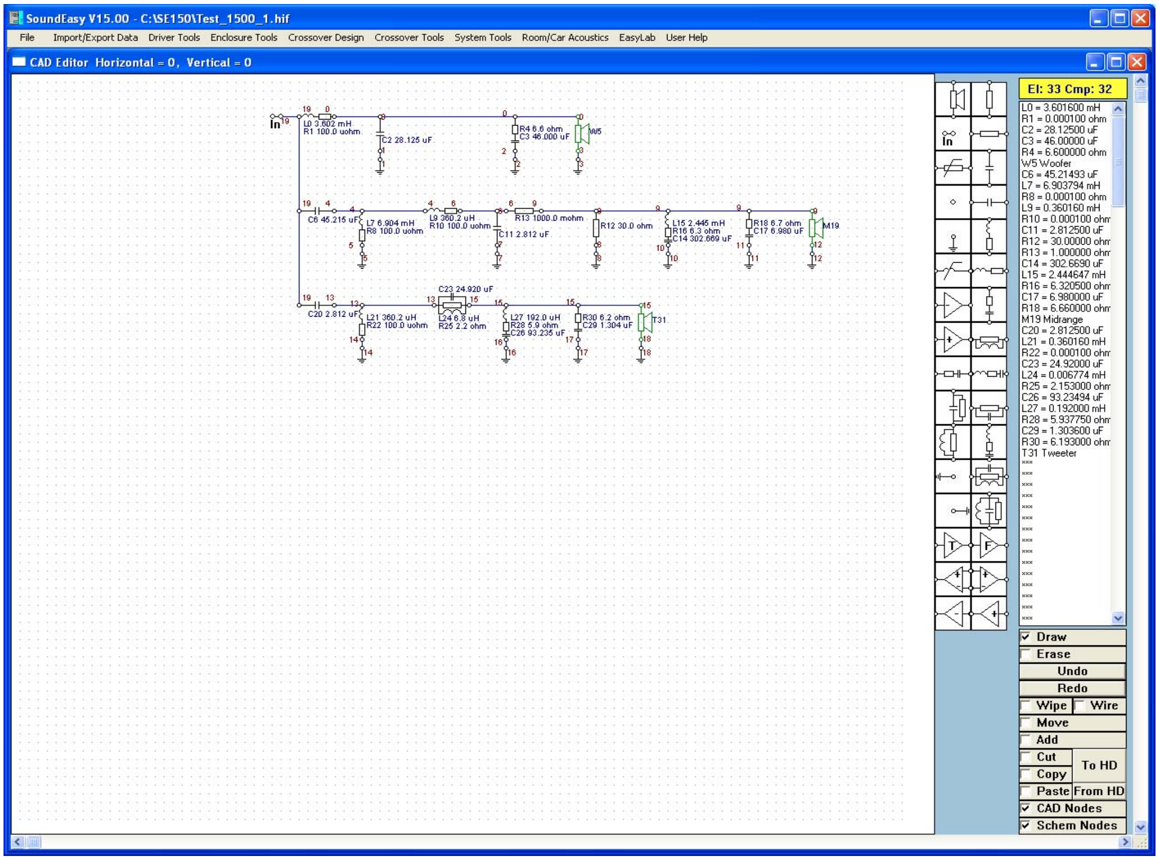


Figure 13.4. Here is our crossover to be optimized.

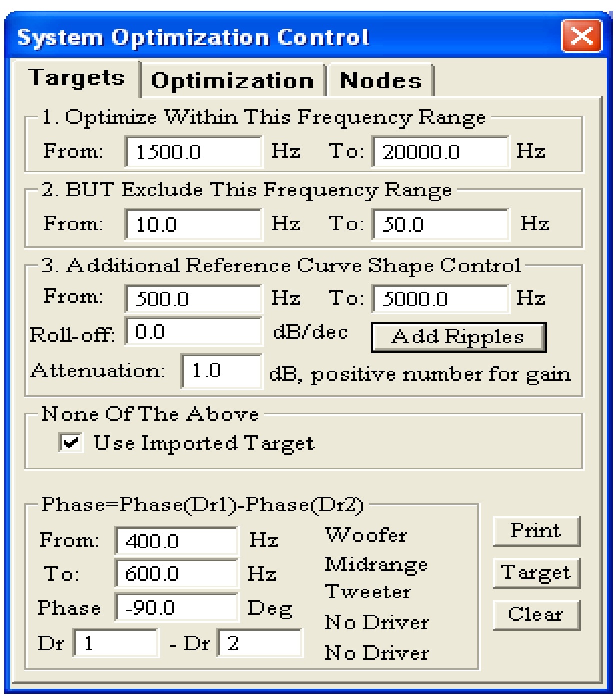


Figure 13.5. Fully preset optimization parameters for the midrange driver

We strongly advocate, that only one driver channel should be optimized at a time. Therefore, we will perform two-step optimization:

1. In the first step of optimization, we will concentrate on the low-pass section of the midrange band-pass filter: L9 = 0.36016 mH and C11 = 2.8125 uF - please refer to Figure 13.4
2. In the second stage of optimization we will concentrate on the high-pass section of the tweeter filter: C20 = 2.8125uF and L21 = 0.36016 mH - please refer to Figure 13.4.

Optimization Results

Figure 13.5 shows fully preset optimization parameters for the midrange driver and Figure 13.6 shows the results of optimization. Please note, that **SPL Error = 565 after midrange optimization.**

If you were to finish the optimization now, you would press "Accept New Values" button, so the SoundEasy can use these new values in other screens.

Figure 13.7 shows fully preset optimization parameters for the tweeter driver and Figure 13.8 shows the results of optimization. Please note, that **Global Error = 285 after tweeter optimization.**

Again, **PLEASE PRESS the "Accept New Values" button now, so the SoundEasy can use these new values in other screens and later save them into the project file.**

In order to visualize the improvement, please consider Figure 13.9. The lower plot is the "Before" and upper plot is the "After" optimization result. Clearly, the frequency response is significantly flatter. It is always recommended to check the frequency response of individual filter AFTER OPTIMIZATION to check if the basic filtering characteristics of the crossover still hold. Also, the input impedance (Figure 13.8) is quite stable, therefore at this point of time, we would conclude that **optimization process met our initial requirements of maximally flat response above 1.5 kHz**.

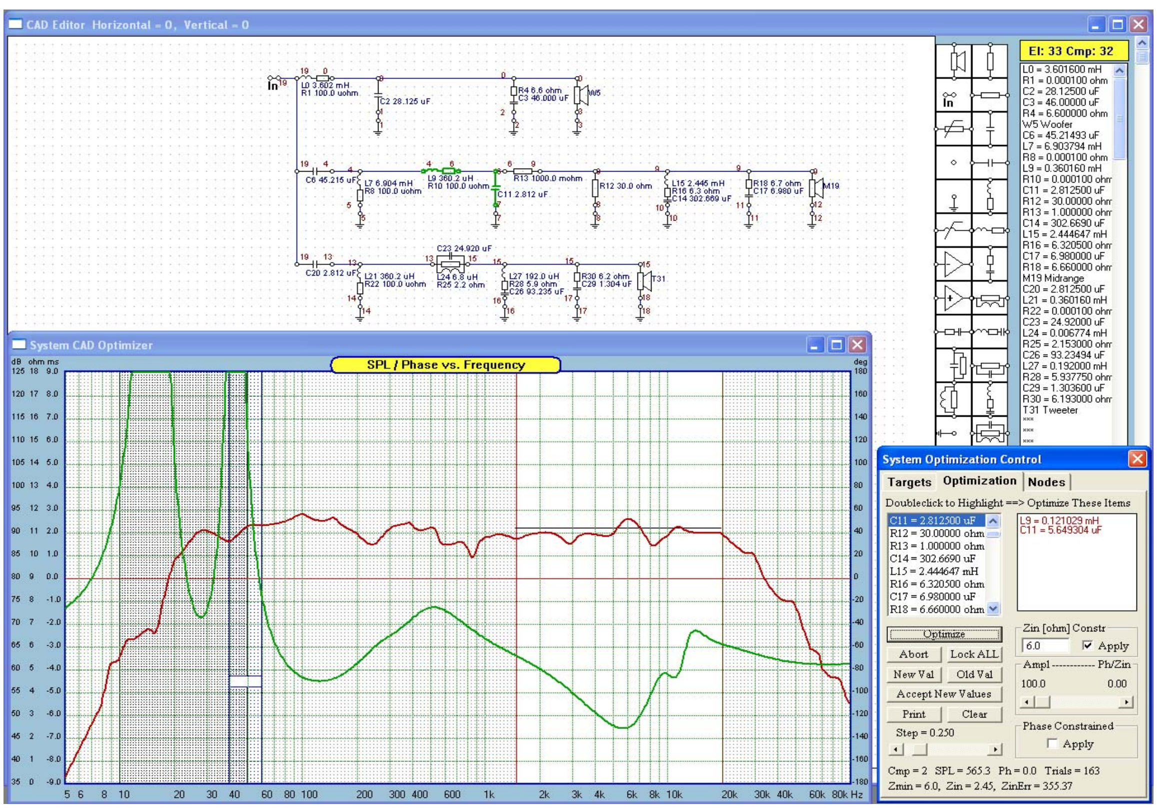


Figure 13.6 Results of the midrange driver optimization.

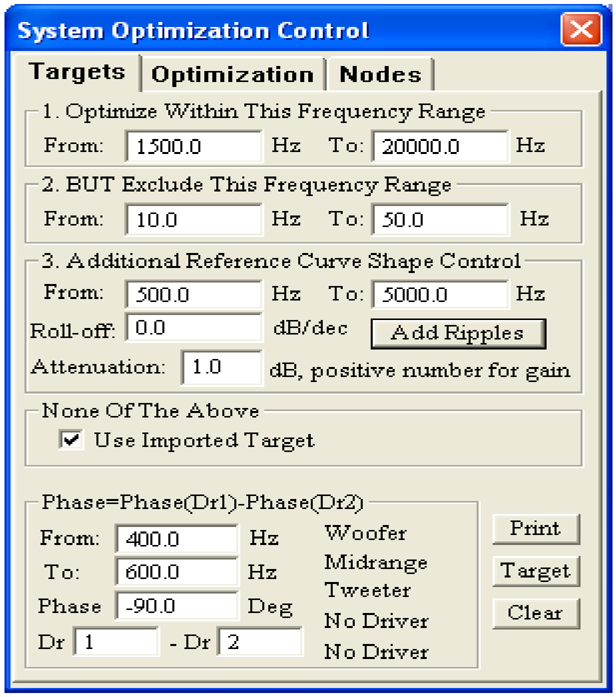


Figure 13.7. Fully preset optimization parameters for the tweeter driver

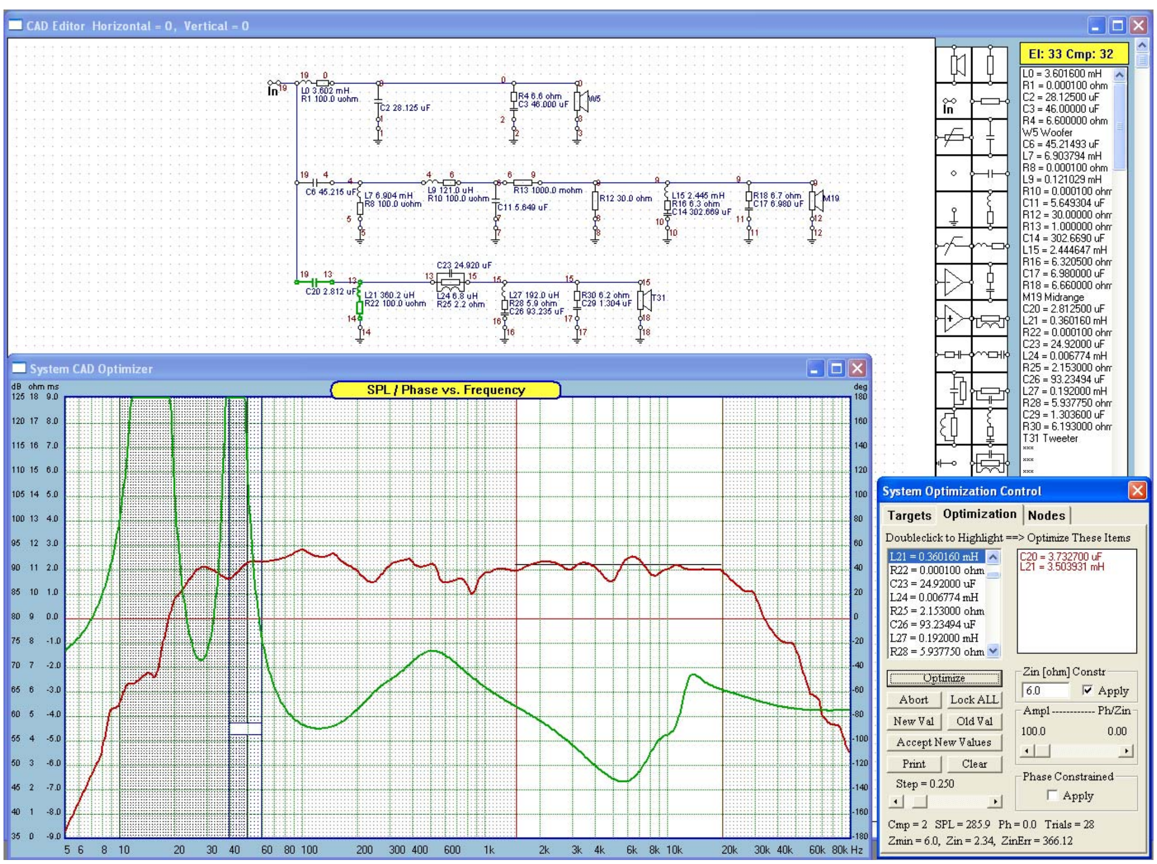


Figure 13.8 Results of the tweeter driver optimization

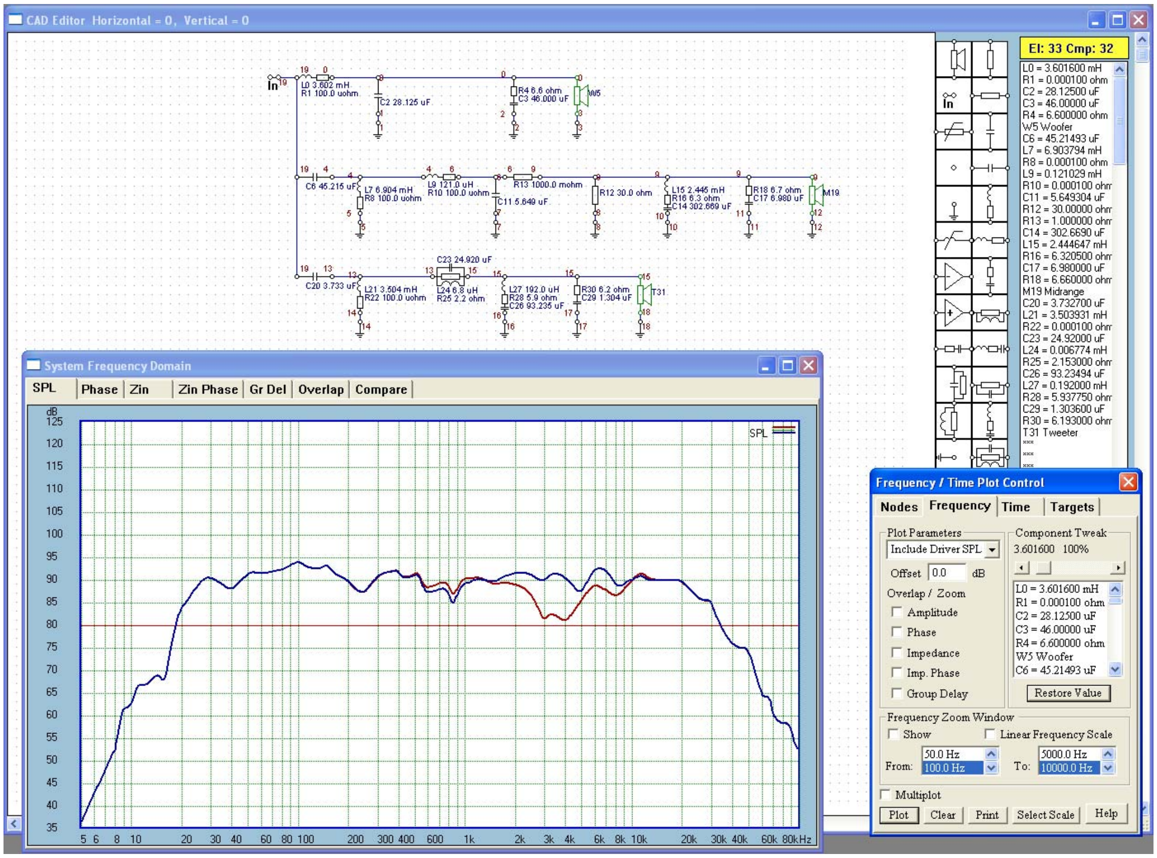


Figure 13.9 Final comparison of "Before" (red) and "After" (blue) optimization.

Final Comments On Optimization

Next step is to critically examine the final component values of all the filters and their final frequency responses. Please remember, that crossover filter must also protect the driver from out-of-band frequencies and drastic deviation from the required shapes may not be in the best interest of the system power handling point of view. You are strongly encouraged to experiment with the optimization tools. A fast computer may be a definite advantage as it will shorten the optimization time. Two examples were given, one in Chapter 10 and one in Chapter 13 to illustrate the selection of the optimization frequency range. The designer needs to take into account the following factors:

1. The crossover point.
The selected frequency range needs to overlap the adjacent filter in order to perform the optimization properly, but excessive overlap is not recommended.

If the overlap is excessive, it will increase the optimization time and may cause some problems since the algorithm will try to compromise the degree of fit between the useful frequency range and the excessive overlap. Also, if the channel output falls below -15 or -20 dB below the nominal level, the driver contributes very little to the system and there is no need to Optimize beyond this level.

2. The optimization time.
Generally, the wider the range, the longer it will take to complete optimization.

3. The required flattens of the system frequency response.

As mentioned in Chapter 1, all optimization tools modify the data and the results need to be saved back to the data file.

Optimization algorithm.

Rosenbrock's "Rotating Coordinates Method" has been around since 1960. It is one of the most robust methods available for optimization when the derivatives are not available. This program implements the algorithm for the purpose of finding a minimum value of an error function of n variables; f(n1,n1,n3......nn). The error is understood as positive or negative deviation from a reference function, which in our case is user selected reference frequency response of a given filter. The total error is calculated as follows:

$$f(n) = \sum_{k=1}^{520} (f_{resp}(k,n) - f_{ref}(k))^2$$

where: $f_{freq}(k,n)$ is the currently calculated frequency response,

$f_{ref}(k)$ is the user selected reference filter frequency response.

Summation is performed for all discrete frequency steps k=1...520. There is 'n' components (variables) in the crossover filter. Practically, the algorithm, operating in n-dimensional space, is attempting to find the shortest way from current location, defined by component values, to a new location, where the error function would ideally assume global minimum. From a current location, the algorithm is making 'n' trial moves in specifically calculated directions, with specifically calculated steps. The error function is calculated in every direction and care is taken to make sure, that every direction has been checked with a successful step (reduction in error) followed by failure (increase in error). The direction of the smallest error is then rewarded by increasing the step in this direction by 3 times. Finally, the whole coordinate system is aligned with the direction of the smallest error such a way, that the first coordinate is aligned with the direction of the smallest error. As one can observe, calculation of directions, rotating the system and calculation of step size becomes the focal point of the algorithm.

Gram-Schmidt ortogonalization process for finding directions is employed. In order to construct 'n' mutually perpendicular vectors (directions) **ξ1**, **ξ2.....ξn**, supporting vectors **A1, A2......An** are constructed first:

A1 = (a1, a2...........an)
A2 = (0, a2...........an)
.....
An = (0, 0, 0,an)

The first direction ξ1, is found by normalizing **A1.**

$$\xi_1 = \frac{A1}{\left[\sum_{i=1}^{n} a_i^2\right]^{1/2}} = (\xi_{11}, \xi_{12}, \ldots\ldots\xi_{1n})$$

In the next step, **A2** is used to construct a vector **B2** normal to ξ1,

$$B2 = A2 - \xi_1\left[\sum_{i=1}^{n} \xi_{1i} a_i\right] = (b_{21}, b_{22}, \ldots\ldots\ldots b_{2n})$$

B2 is then normalized to obtain the second direction **ξ2**,

$$\xi_2 = \frac{B2}{\left[\sum_{i=1}^{n} b_{2i}^2\right]^{1/2}} = (\xi_{21}, \xi_{22}, \ldots\ldots\ldots\xi_{2n})$$

B3, ξ3, **B4, ξ4**, are calculated in the same manner. Generally, direction **ξk**, is found as:

$$Bk = Ak - \xi_{k-1}\left[\sum_{i=1}^{n} \xi_{k-1} a_i\right] = (b_{k1}, b_{k2}, \ldots\ldots\ldots b_{kn})$$

$$\xi_k = \frac{Bk}{\left[\sum_{i=1}^{n} b_{ki}^2\right]^{1/2}} = (\xi_{k1}, \xi_{k2}, \ldots\ldots\ldots\ldots \xi_{kn})$$

Pre-Distorted / Tilted Frequency Response

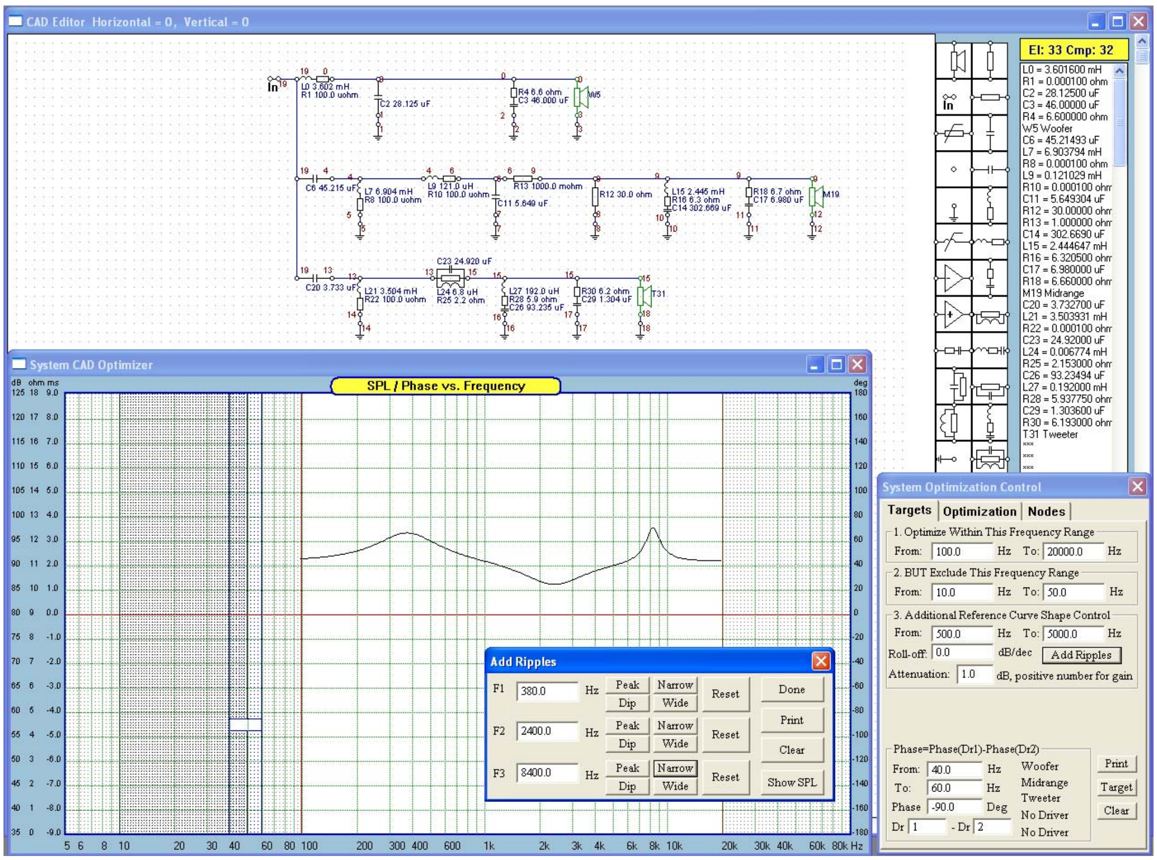


Figure 13.10. Various options for pre-distorting the target frequency response.

At times, you may wish to experiment with system frequency response, that is dropping toward higher end. Some systems may be particularly prone to these characteristics, such as WMTMW arrays. Here, the two woofers could add as much as 6dB to the efficiency of the system, while the midrange drivers contribute only 3dB. This may be the exact advantage you are looking for in the system. Obviously, selecting less efficient woofer/midrange drivers restores the balance. In a station like this, a smooth transition between the drivers can be achieved by tilting the frequency response by some fixed amount of dB/decade (NOT dB/oct).

Amplitude optimization alone will produce flat frequency response at the expense of phase relationship between adjacent drivers. This phase relationship, determines vertical radiation pattern around the crossover frequency. You could easily end-up with drastically different properties of your system, and really lose control over this important property of your crossover if the phase is allowed to be modified too much by the SPL optimization process alone. However, including phase in the optimization parameters, will prevent it from being excessively modified.

Even better, you can assign more importance to the phase (by moving the slider to the right) and actually have the phase relationship improved around the frequency band of interest. Changes in the vertical radiation pattern are the best observed using "System Polar/Line Plots" dialogue box. System optimization process can be now quite involving and often you may find yourself running the optimizer several times in order to explore various settings for phase, Zin and SPL. **Finally, we suggest, that you will select "Include A/Center + Z-Offsets in Plots" option on the system "Front Panel Layout" screen to reduce the number of phase reversals on the phase difference plot.**

Adding Ripples

In addition to the above pre-distortion, three "ripples" can be added to the target curve. Each ripple can be a peak or a dip in the frequency response. In order to incorporate the ripples into the target curve, please select "Add Ripples" button on the "Optimization Control" dialogue box. This dialogue will be replaced with smaller control box "Add Ripples" allowing you to control all parameters of the newly introduced ripples:

1. **Width** of the ripple – use "Narrow" or "Wide" buttons.
2. Location on the **frequency** scale – enter frequency in the "F1", "F2" or "F3" data field.
3. **Height or depth** of the ripple – use "Peak" or "Dip" buttons.
4. **Cancellation** of the ripple – press "Reset" button.
5. **"Show SPL" – use this button to plot SPL with current optimized values.**
6. The "Clear" button will clear and re-plot the target curve on the main optimization screen.
7. Finally, when you are happy with the result, press "**Done"** button to close the "Add Ripples" dialogue box. All parameters of the ripples are saved to the data file.

Constrained System Optimization

Generally, Constrained Optimization involves gaining some desired circuit parameters, namely inter-driver phase response or minimum input impedance of the circuit, and giving up some accuracy in SPL optimization.

Component Type Selection

It is essential, that you select components that are meaningful to the goal of your optimization. Failure to do so simply defeats the whole optimization process. Therefore, if you are uncertain as to what components are best suited for this particular goal, it may be best for you to learn more about the circuit you are dealing with first.

More advanced circuit designers will have no problems here. If you are not one of them, then you may try to go back to the CAD system and play with component values to see what changes in SPL/Zin/Phase when you tweak particular component. This is a learning process, and may not give you ready-to-go answers, but it will give some clues for component selection. Obviously, the in-depth circuit knowledge is invaluable at this process. It is recommended, that you DO NOT try to optimize more than 2-3 components at a time.

For best results in the system optimization process, it is NOT advisable to optimize components, which belong to different drivers. You should restrict component selection to single driver, and run the optimization. Then you can try another driver separately – but NOT both.

In a 2-way system, you would typically lock tweeter components and work first with woofer filter. This way, woofer channel frequency response has to stay compliment to the tweeter, in order for the system SPL to stay flat. This would assure, that woofer hast to stay as a low-pass filter during optimization – even though you can not see individual driver frequency response.

Phase Constrained Optimization

Radiated sound pattern at the crossover frequencies is affected by phase relationship between adjacent drivers. It may be desired, that the phase difference between those drivers at the crossover frequency, falls between certain predetermined levels. For instance, in a 3-way system, consisting of woofer, midrange and tweeter drivers, you would consider phase relationship between woofer + midrange and midrange + tweeter. Obviously, woofer and tweeter would be so far away from each other in terms of their assigned frequency bands, that their radiation would not affect each other.

This process is guided by assigning certain weights (or importance) to SPL vs. Phase. There is a slider bar provided on the TAB for the purpose of assigning anything between 0% - 100% for SPL and Phase. The slider works on the principle, that "what you take from one parameter, it gets assigned to the other". So 100% is split between SPL and Phase.

It is immediately obvious, that assigning 100% to SPL makes it "Unconstrained SPL" optimization. And conversely, assigning 100% to Phase, makes it "Unconstrained Phase" optimization.

An example of Phase Constraint, could be a requirement of 0deg phase difference at the crossover frequency between woofer and midrange drivers.

1. First, please make sure, that you SPL target is set correctly for frequency range and the target level on the "Target" TAB.

2. On the "Targets" TAB, you can set up the optimization process to look only at the frequency band around the crossover frequency. Then assign drivers involved as woofer and midrange, and finally set the "min" and "max" phase levels for optimization.

3. Then on the "Optimizer" TAB you should check the "Phase Constrained" check box. You will observe, that the "Zin Constrained" check box is automatically "unchecked".

4. Finally, set the slider initially to SPL = 90% and Phase = 10%, and start Optimization.

Most likely, the optimization process will not achieve the desired phase response, but this first step is mainly to make sure, that the whole process has been set-up correctly and is running correctly. You can now try to assign increasing weight to "Phase" and observe the resulting optimization. You should be able to observe the phase between nominated drivers getting closer and closer to the desired range.

Zin Impedance Constrained Optimization

Input impedance of the crossover, Zin, is not a flat-line curve. It has peaks and dips, sometimes below certain, desired minimum impedance. If you are concerned with these characteristics, you may try to lift the minimum circuit impedance within some frequency band – this is the purpose of Zin Constrained optimization.

This process is guided by assigning certain weights (or importance) to SPL vs. Zin. There is a slider bar provided on the TAB for the purpose of assigning anything between 0% - 100% for SPL and Zin. The slider works on the principle, that "what you take from one parameter, it gets assigned to the other". So 100% is split between SPL and Zin. It is immediately obvious, that assigning 100% to SPL makes it "Unconstrained SPL" optimization. And conversely, assigning 100% to Zin, makes it "Unconstrained Zin" optimization. An example of Zin Constraint, could be a requirement of 6ohm minimum input impedance within 500Hz – 5000Hz.

1. First, please make sure, that you SPL target is set correctly for frequency range and the target level on the "Target" TAB.

2. On the “Targets” TAB, you can set up the optimization process to look only at the frequency band of interest.

3. Then on the “Optimizer” TAB you should check the “Zin Constrained” check box. You will observe, that the “Phase Constrained” check box is automatically “unchecked”.

4. On the “Optimizer” TAB, enter the desired minimum impedance, say 6 ohm.

5. Finally, set the slider initially to SPL = 90% and Zin = 10%, and start Optimization.

Most likely, the optimization process will not achieve the desired Zmin response, but this first step is mainly to make sure, that the whole process has been set-up correctly and is running correctly. You can now try to assign increasing weight to “Zin” and observe the resulting optimization. You should be able to observe the input impedance is getting closer and closer to the desired level.

An important feature of the “Zin Constrained” optimization algorithm, is that attempts to bring the input impedance as close to the specified impedance as possible. So the result may be an input impedance, that is slightly below specified impedance, OR slightly above it. This way, the process is prevented from “runaway conditions”, and you would not end up with circuit impedance 3 times the minimum – simply because it’s greater than the minimum.

Example below explains Zin Constrained optimisation using R13=1.0ohm to rise the input impedance to around 6.0ohm in 600 – 3000Hz frequency range.

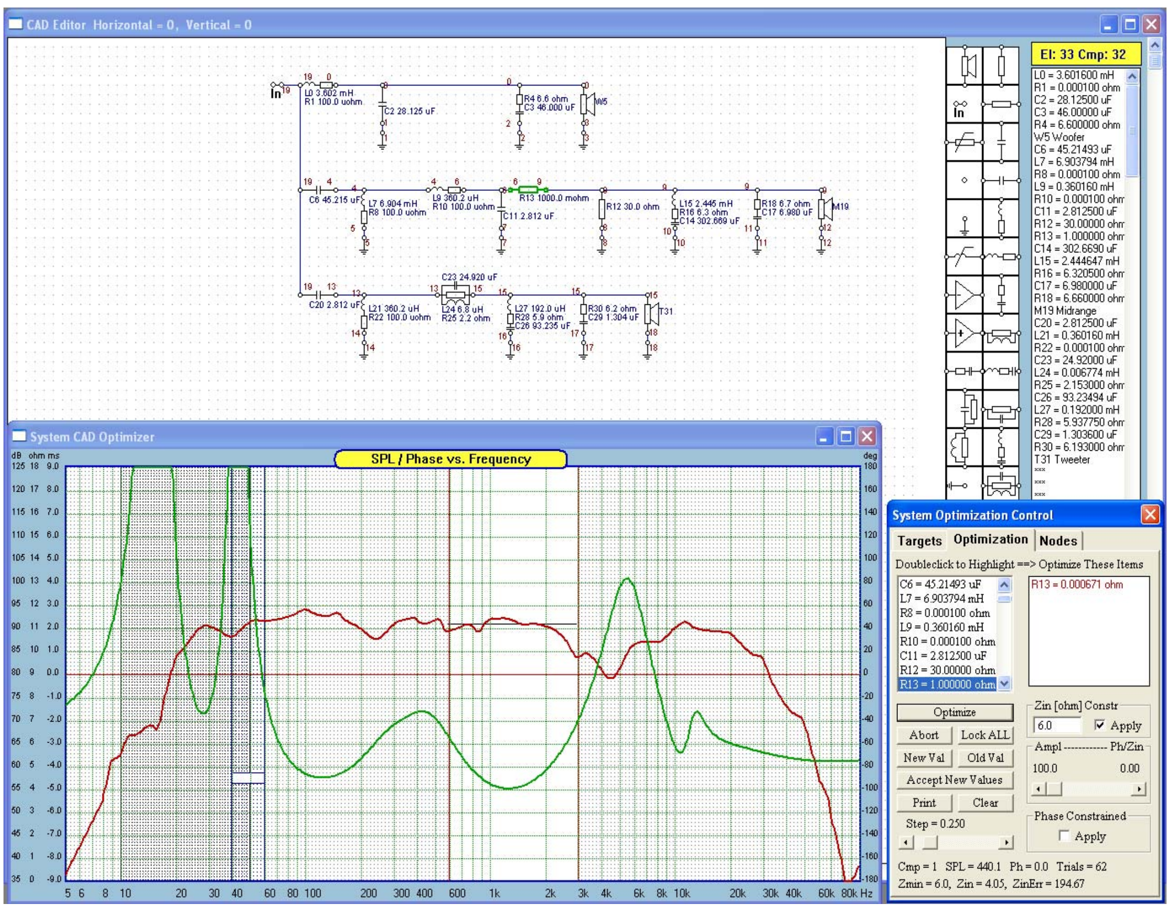


Figure 13.11. Optimization result for AMPL = 100% and ZIN = 0%. Zin = 4.05ohm

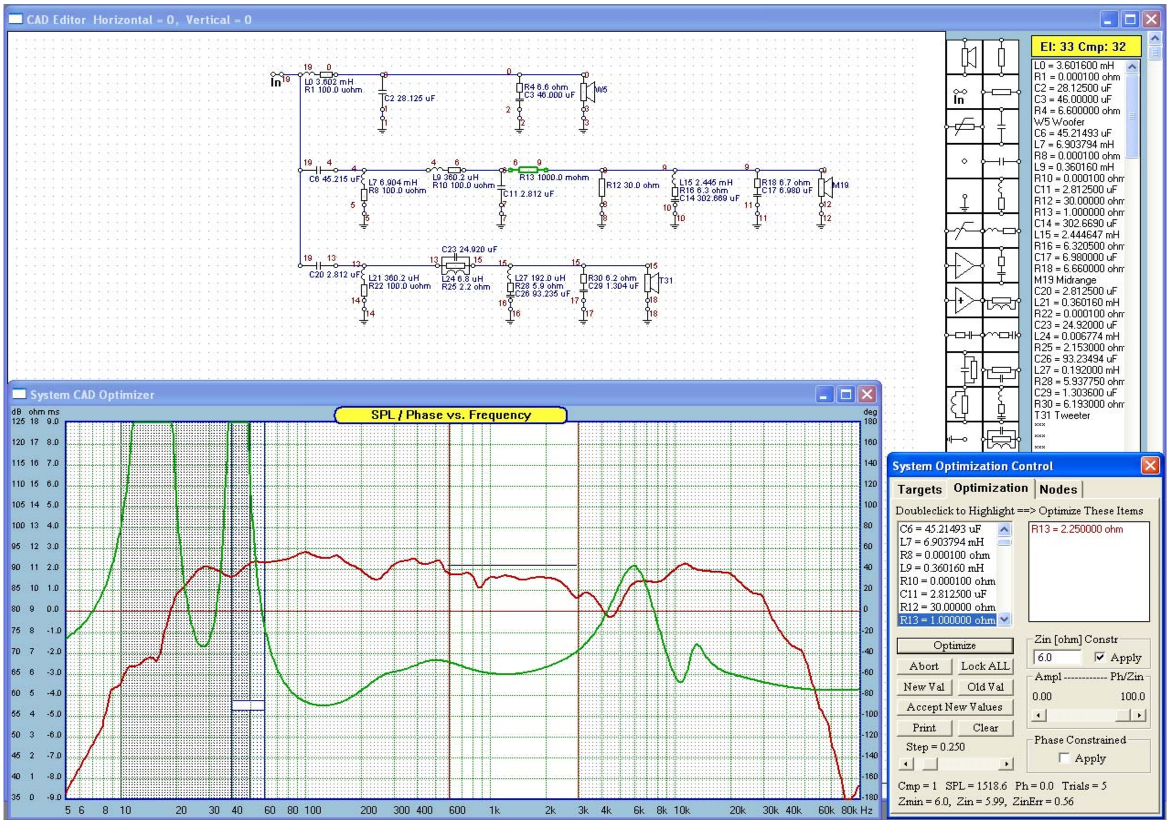


Figure 13.12. Optimization result for AMPL = 0% and ZIN = 100%. Zin = 5.99ohm.

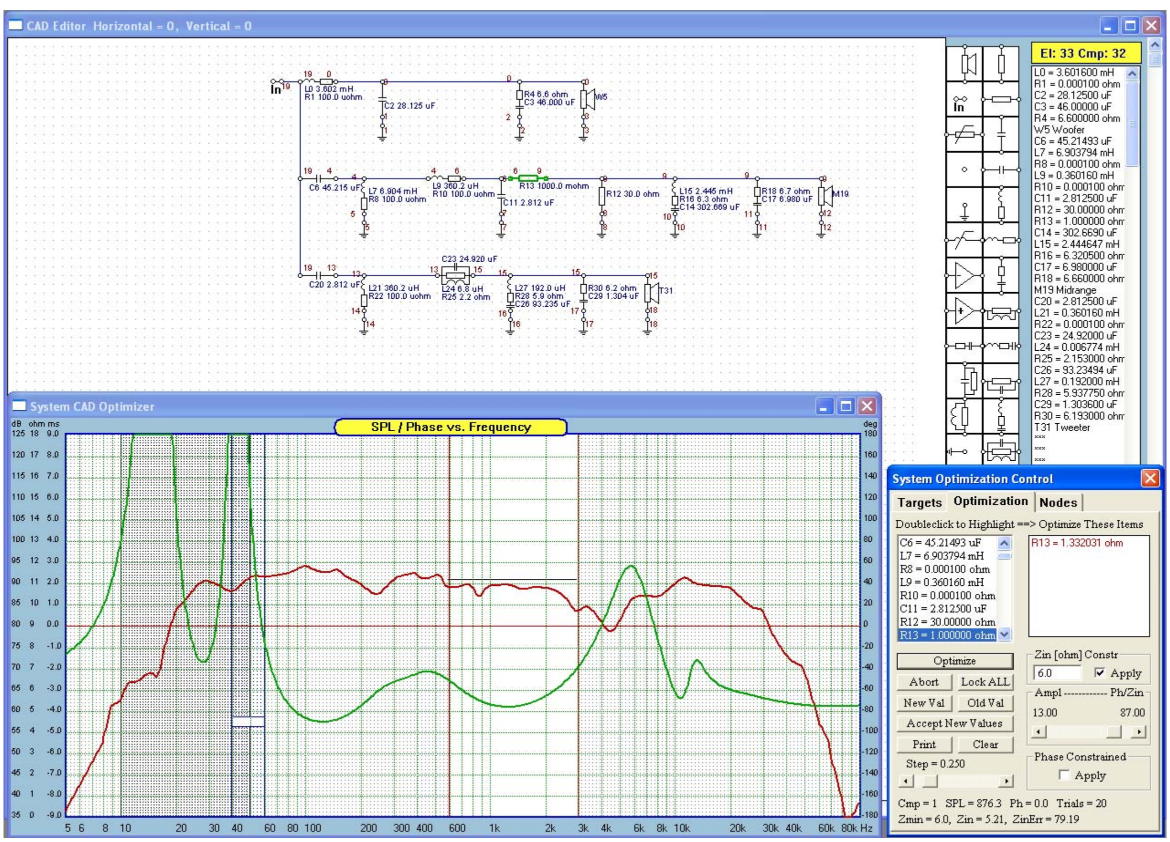


Figure 13.13. Optimization result for AMPL = 13% and ZIN = 87%. Zin = 5.31ohm.

Nominating Components From Schematic

All unlocked components for optimization will appear in the “Optimizer” TAB display field. The field can display up to 10 components, but it is never recommended to optimize more than 2-3 components at a time. The TAB also contains a component list box, where you can select components for optimization. Double-clicking LMB will transfer the required component into the display field, thus confirming, that the component is UNLOCKED, and ready for optimization. The component will stay highlighted in the list box as well. If you are dealing with a large schematic, the list box will be filled and you will have to scroll it, in order to bring the desired component into view. This process can be automated. While the “Optimizer” TAB is selected, and the Optimizer plotting window is opened, you can click LMB on any component on the schematic and this will automatically scroll the TAB list box such a way, that the nominated component is at the top of the list in the box. You can now double-click LMB and consequently transfer the required component into the display field, thus confirming, that the component is UNLOCKED. The component will stay highlighted in the list box as well, and the selected component on the schematic will turn green.

In short, the rules are simple:

1. UNLOCKED components are displayed in the “Optimizer” TAB display field, and the components will stay highlighted in the list box as well.
2. The selected component on the schematic will turn green.
3. To LOCK the component, simply double-click on the HIGHLIGHTED component in the “Optimizer” TAB list box. This will remove the component from the display field and remove highlighting of it from the list box.

In fact, all UNLOCKED components (components, that will be used for optimization) will be displayed on the schematic in bold, green colour. They are now very easily identifiable on the schematic.

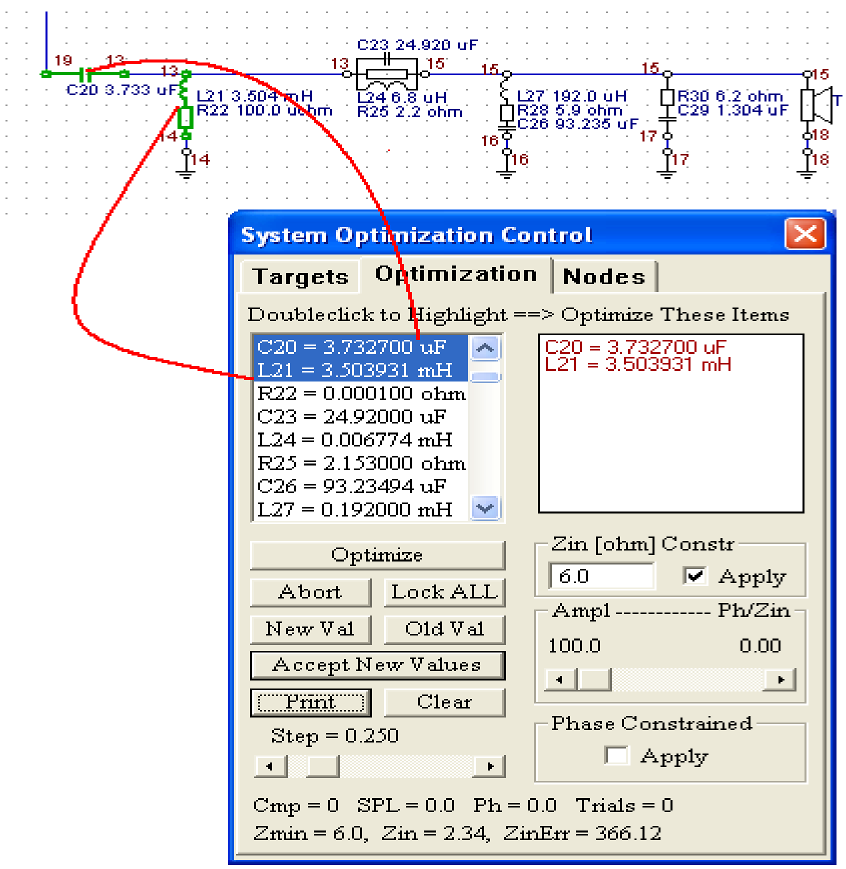
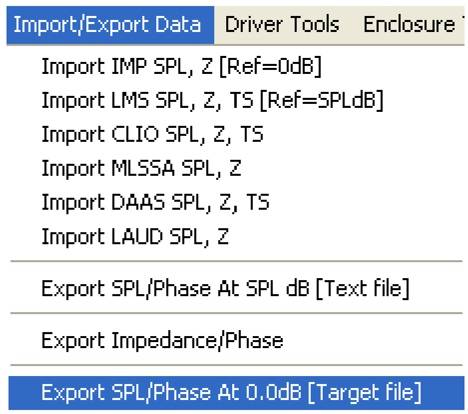


Figure 13.14. Selecting and Highlighting components.

User Defined Simple Target Curves

Target curve without phase information (only SPL data) can be instantly created and exported, while you are in the "Targets" TAB of the optimizer. Simply edit your target SPL curve the way you need it, and while you are in the "Targets" TAB, select **"Export SPL/Phase At 0.0dB [Target file]"** sub-option from the main menu oftion of "Import/Export Data" – see below.



The last edited SPL target curve will be save to the nominated data file, and will be saved without any phase information.