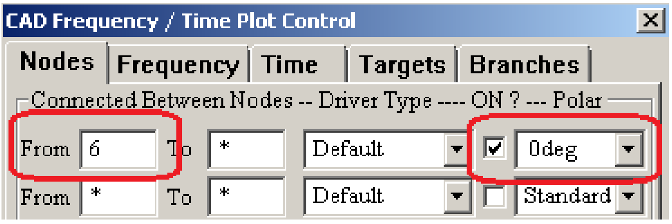
Chapter 10. Filter/Crossover Optimization

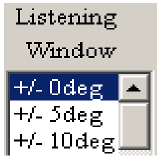
Classical approach to crossover filter design is based on electrical filter theory. Therefore, the filter transfer functions and component values calculated from the filter theory should only be used to construct the first approximation of the crossover filter. The final values of the components should be only decided upon after the optimization of the filter has been performed and it produced satisfactory improvement in the filter performance. This task has been assigned to the optimizer screen. The default window of the tool with the main control box is shown on Fig 10.1, where an example data file has been loaded and displayed on the screen. Optimization process does not involve moving the microphone around or rotating the enclosure, or any mechanical adjustments affecting measured SPL etc… **The optimization is based on measured set of curves, that is now ONLY accessible via the following settings:**



Driver Files now contain fully edited set of SPL curves stored for -90deg …..+90deg angles, and these curves are accessible via the "Polar" angles selection – as shown above. You can now perform Filter Optimization of **Measured SPL** response for any selected angle, or **Listening Window** of any width.

for all measured angles OR

for width of



Optimization

You may decide to optimize only the crossover network component values. It is very likely, that majority of the designs would follow this option. However, since all the passive/active components entered from the CAD screen may be actively involved in the optimization, you may wish for example, to split the compensation network into L-pad attenuator and impedance compensation network for the midrange driver (and lock them) AND crossover components - as the second group of components. The second group will not be locked - the optimizer screen will optimize only the crossover (unlocked) components. Please upload now "Test_1200_1.mid" data file. When the process is completed, select **"Filter/Crossover Optimizer**" under **"Crossover Design**" menu option. The screen that will be opened next will look similar to the one shown on Fig 10.1. Your first step in the optimization process is to select 'From' and 'To' frequency range of the optimization. It is easier to make the decision while looking at the actual frequency response of the selected filter. The frequency response can be plotted using **"Old Values**" button on the "**Optimization**" tab. Upon examination of the responses, we decided to set the 'From' frequency to 200.0Hz and 'To' frequency to 12000.0 Hz. You must now set-up a target response for the optimizer. Operation of this dialogue box has been described on page 10.12. Let's assume, that the target curve shape was selected as a second order (+12/-12dB per octave) Butterworth response and cut-off frequencies have been set to 500Hz and 5000Hz for high-pass and low-pass respectively.

If you now depress 'Optimize' button, the optimization process will commence at the end of which the curves as on the Fig 10.2 will be plotted (you can go ahead and press the 'Optimize' button for the sake of experiment. If you do so, you must press "Old Values" button, when the optimization process is completed). This is not exactly what we expected. The brown line represents the filter response and is badly extended at higher frequencies. The total channel response is however very good. It resembles very well the targeted, 2-nd order Butterworth band-pass filter. To explain the problem please refer back to Fig 10.1. Here we can observe, that initial channel response exhibits already faster roll-off at higher frequencies then the 2-nd order target function. This is due to the fact, that channel response is a combination of the driver and filter responses. Driver's frequency response starts to roll-off around 5kHz and this combined with the selected filter response will produce much faster roll-off than the targeted 2-nd order curve. The program has managed to modify the component values such a way, that the overall response resembles the targeted function, but this result is clearly unacceptable.

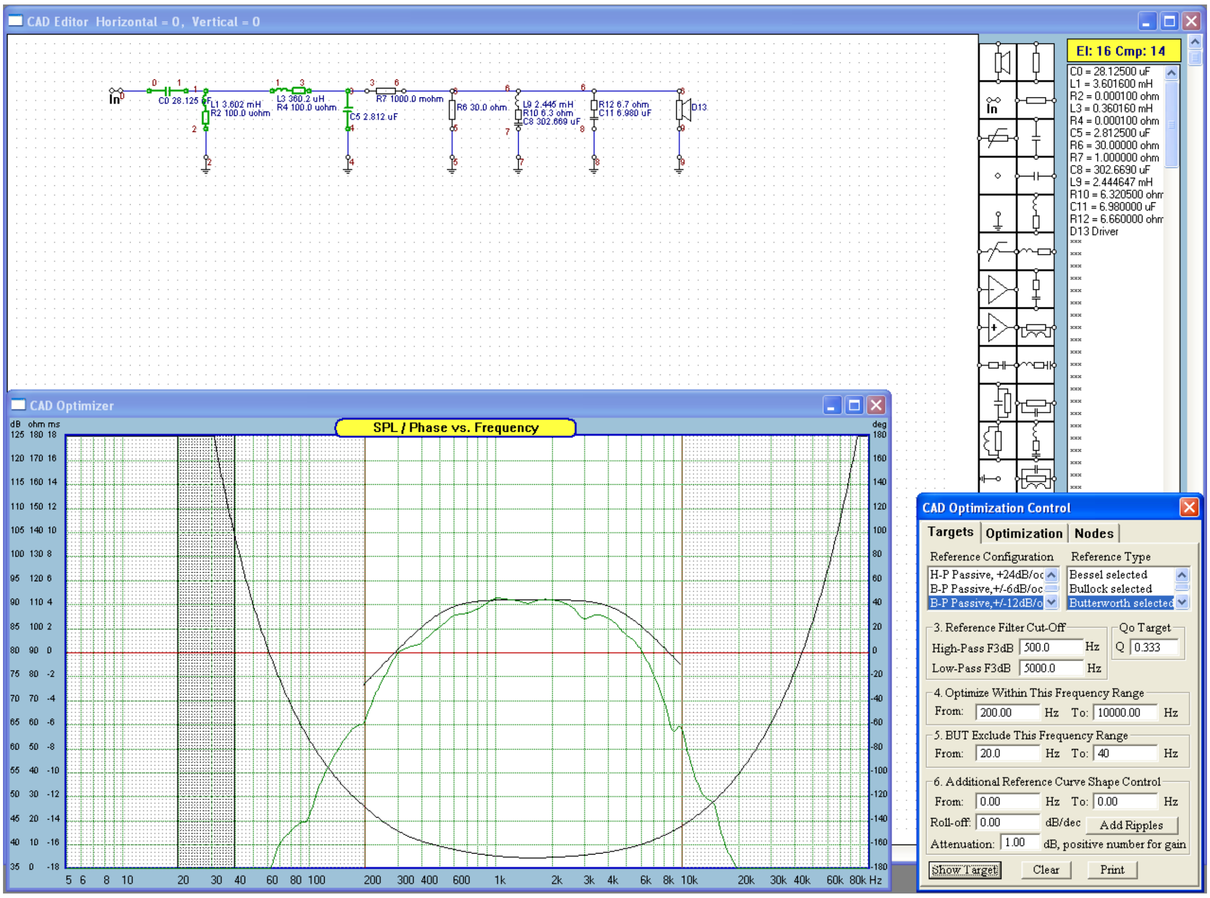


Fig 10.1 Optimization control dialogue box

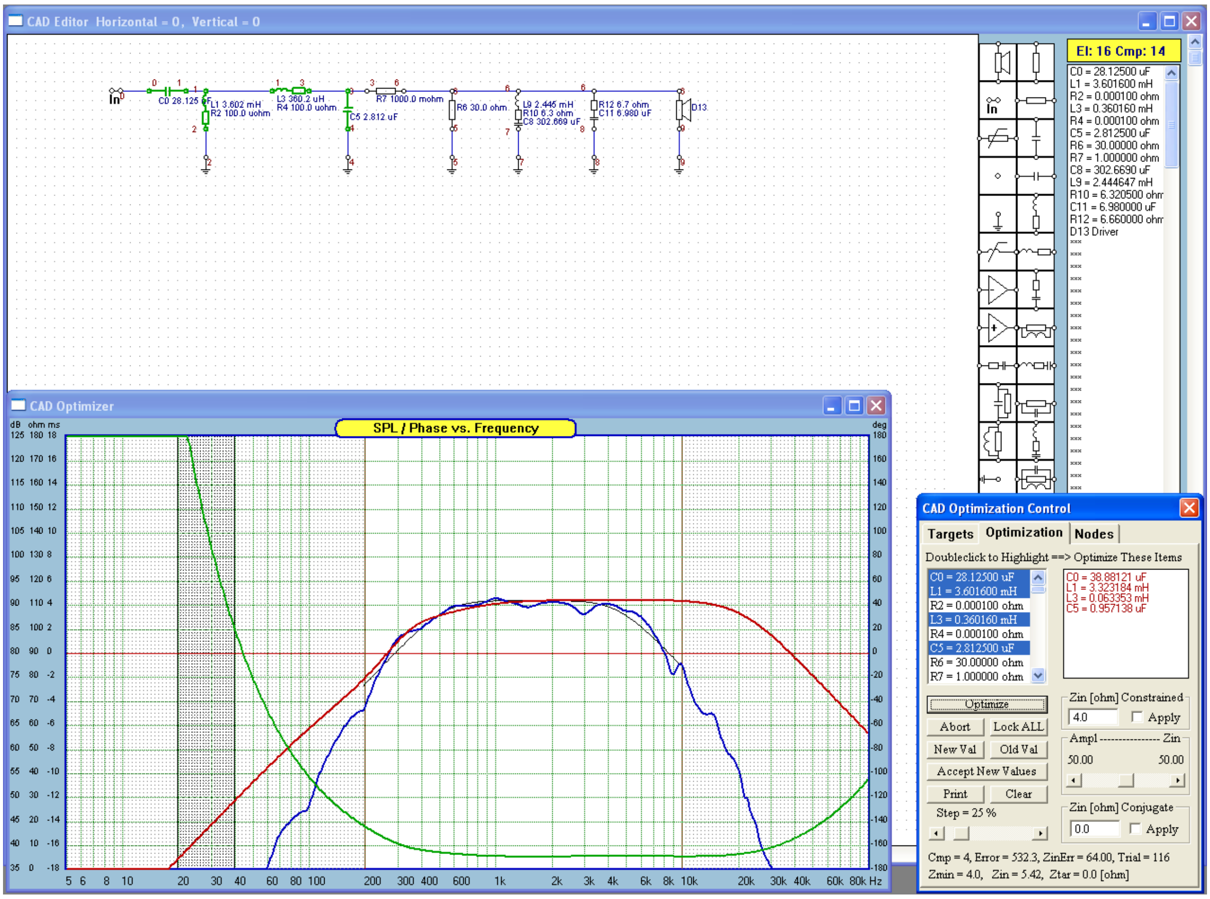


Fig 10.2 The results of wrongly selected optimization parameters

A better solution here would be to target 4-th order band-pass filter as the final response and then perform the optimization. Fig 10.3 and 10.4 show this scenario. Please note, that frequency range of optimization was narrowed because a filter with faster roll-off was selected. Should the old frequency range be kept, the algorithm would be optimizing the response down to -35dB level which is not recommended. When the optimization process is completed, you should obtain plots shown on Fig 10.4.

In case of the test_902.mid driver, its efficiency was 1.5dB higher (92.5dB) then that of the selected woofer (91dB) so that the value of 1.5dB was used for calculating L-Pad (if this is your design goal). Now, the midrange channel efficiency is (92.5-1.5)dB=91dB. This is 1dB over 90dB SoundEasy reference and the same 1.0 dB is now entered in the 'Attenuation' field of the optimizer module. The "Attenuation" parameter indicates, how much we would have to shift the 90dB reference line to match the system efficiency.

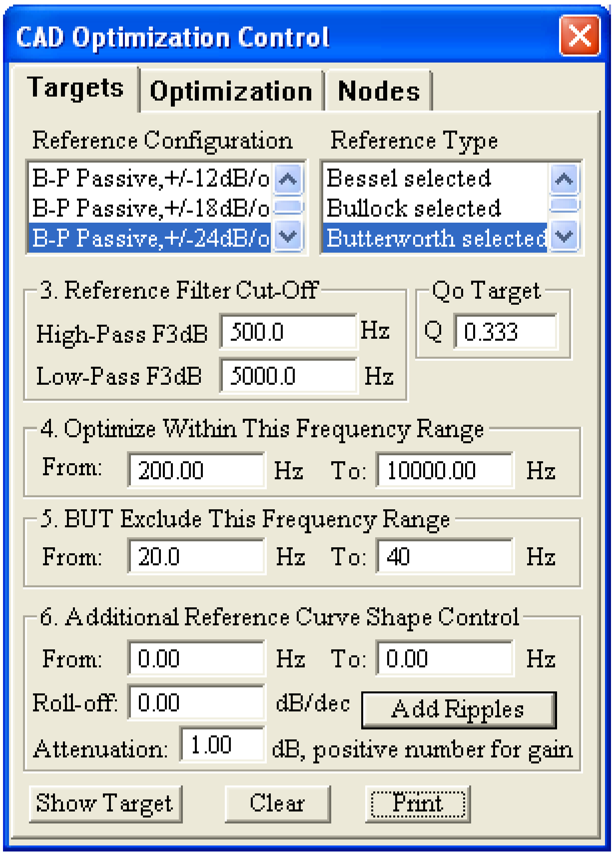


Fig 10.3 Better selected optimization parameters

Selecting Optimization Range

You can edit the boundaries of the optimization range in form of "From" and "To" frequencies. The optimization range will have a great effect on the speed and accuracy of the optimization process. Fig 10.5 shows the woofer driver channel (Test_1200_2.wfr data file) after the optimization. Only the crossover was optimized and Butterworth low-pass filter was used for reference. The optimization process was performed over 50 - 2000 Hz frequency range. In order to estimate the frequency range, click on "Use Original Values" button on the main optimization screen. The complex transfer function of the driver will be plotted on the screen. Next, select the targeted frequency response. Having these two curves on the same screen, you can observe, that above 2000Hz the curves differ significantly. The driver's transfer function rolls-off more rapidly and in order to bring it closer to the reference frequency response, some gain would actually be needed. The driver's output is only 20 dB below the nominal level and the driver would contribute very little to the overall system frequency response.

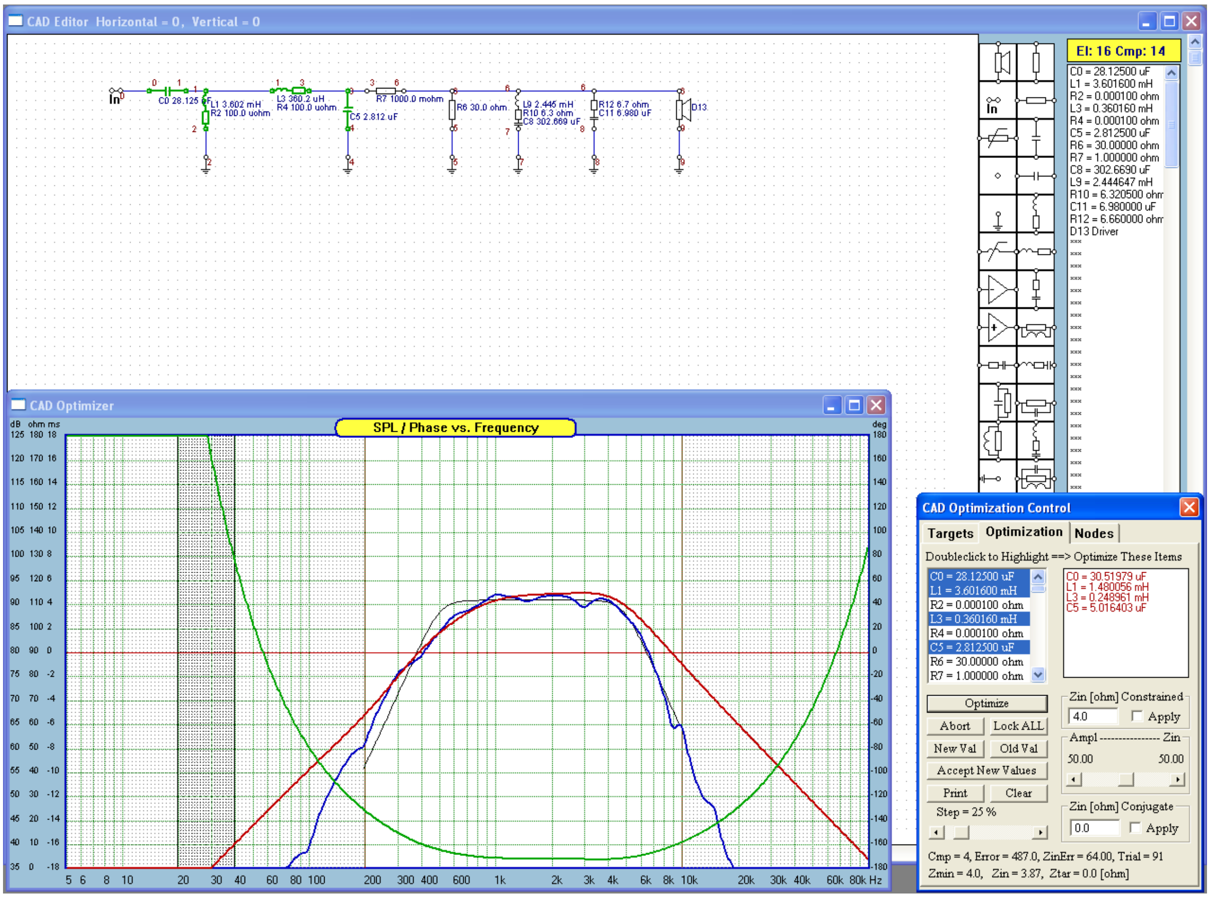


Fig 10.4 The results of better selected optimization parameters

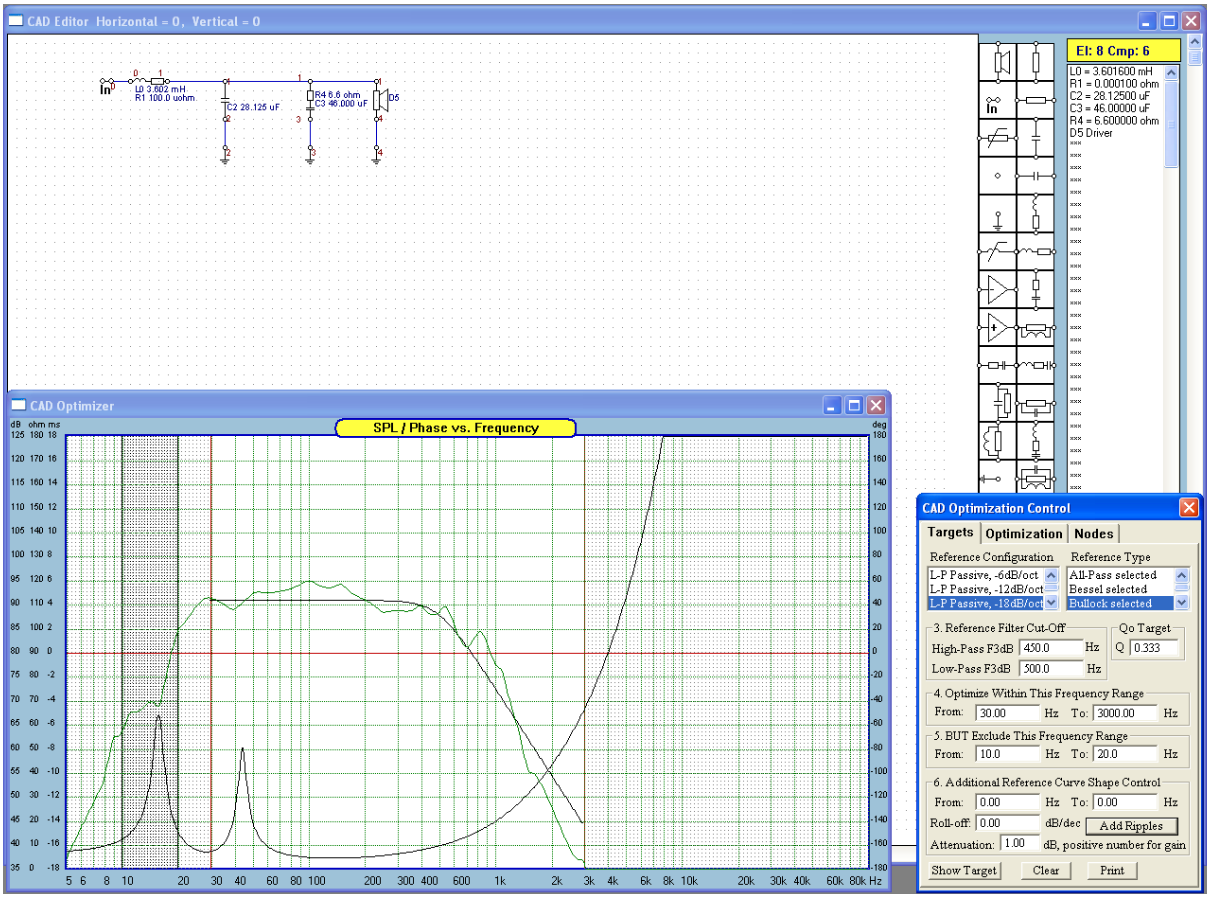


Fig 10.5 Dialogue box showing proposed optimization parameters

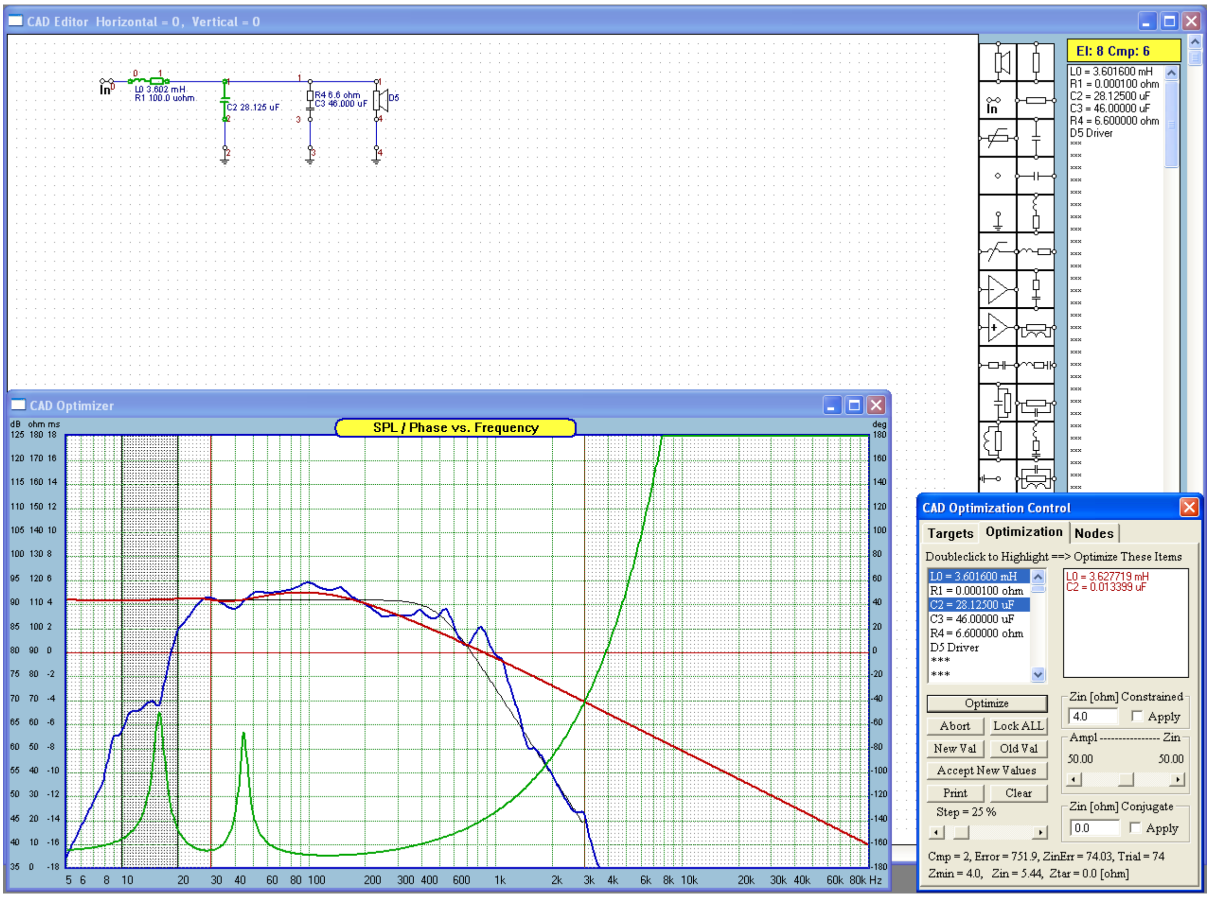


Fig 10.6 Results of the optimization + new filter response (brown).

If the frequency range above the 2000 Hz mark is included in the optimization process, the algorithm used would attempt to compromise frequency response within the useful frequency range, that is 50 - 2000Hz, in order to minimize error between 2000 -3000Hz. This is a highly undesirable situation and can be a source of significant errors in the optimization process. It would therefore be more sensible to select even narrower frequency range eg: 20 - 1200 Hz for the optimization range. In this example, a woofer driver was taken into consideration, but the described method of selecting the optimization range can be applied to other drivers.

It is always recommended to vary the optimization boundaries and perform two or three optimizations and inspect, at least visually, the degree of fit between the target response and the total channel frequency response. If you wish the restart the optimization process always from the same starting conditions (component values), which is recommended you must not save the previous values and re-load the data file each time prior optimization. Save only the results you want to be used by the next module. You can also EXCLUDE a frequency range from optimization. Simply specify the “From:” and “To:” frequencies in the “Exclude” frequency range box – see Fig 10.3.

Additional Shape Control

All reference target curves can be pre-distorted by adding a slope or plateau to the basic shape of the filter. Fig 10.7 shows an example of pre-distorted, -24dB/oct Butterworth filter. The distortion was generated as follows:

1. “Attenuation” was entered as 10dB, therefore, the whole curve is shifted up by 10dB.
2. From 20Hz to 100Hz the frequency response rolls-off by 15dB/dec.

One (but not only) possible application of the pre-distortion is to deal with diffraction distortion. Diffraction distortion typically causes the SPL curve to rise from around 200Hz and flattens around 5kHz (depending on the geometry of the enclosure). Therefore, you may aim to have your crossover designed and optimized around the diffraction distortion. The **“Roll-off”** field accepts positive number for creating rising edge and negative number for creating slopes. Also, the **“Attenuation”** field can be used to add gain – enter positive number or loss – enter negative number.

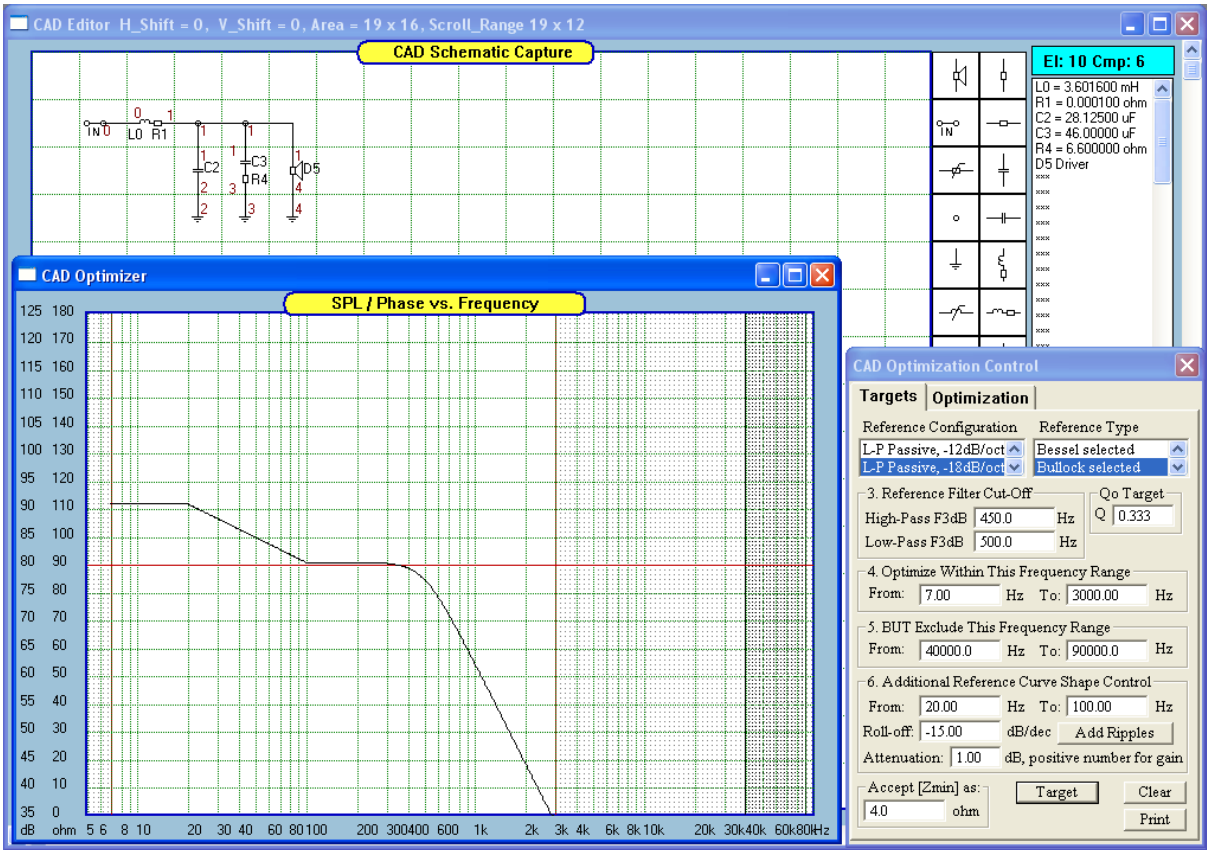


Fig 10.7 Additional shape control – pre-distorted filter

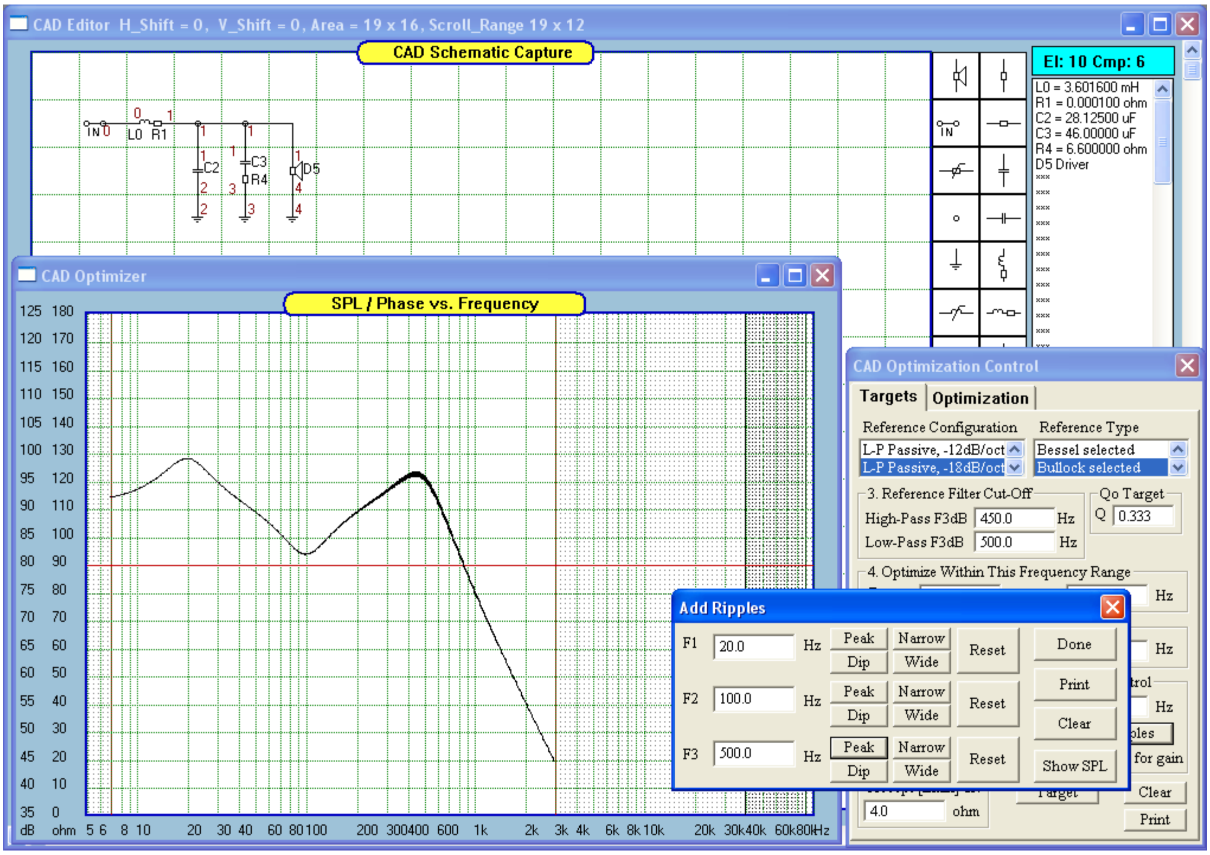


Fig 10.8 Additional shape control – adding ripples

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 display the plot SPL with optimized values.**

The "Clear" button will clear and re-plot the target curve on the main optimization screen. 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.

Locking components.

It is recommended, that you optimize as few components at a time as possible. Typically, no more than 2-3 components, unless you are confident, that larger numbers is necessary. In order to tell the program, which components are to be **included** in the optimization process, you must **DOUBLECLICK** on the required component, listed in the **"Optimization**" tab list box. The selected item becomes highlighted and also the component value is transferred to the display field on the right. All components, that are NOT highlighted and do not appear in the display field are LOCKED.

There is no need to scroll the list box in order to bring the required component into the box display area. Single LMB click on the desired component on the CAD schematic will automatically scroll the list box and will bring the selected component to the top of the list box.

In summary, **DOUBLECLICK** in the list box on the component you wish to include in optimization process. Corresponding items become highlighted automatically. By doing this again, you **TOGGLE** components from OPTIMIZE to LOCK. The lock/unlock status table of each component **is saved in the data file** and the default value is "Optimize" for all components. Notice, that the UNLOCKED components are highlighted in bold green color on the CAD schematic for easy identification.

Optimization routine will terminate if two consecutive trials do not reduce global error by arbitrarily small amount. Since active crossovers employing negative feedback are quite immune to variations in gain, it is highly advisable to lock the gain of the amplifier as it would cause the optimizer to terminate.

Filter Optimization Example

We assume to following:

1. Woofer efficiency, η woofer = 91dB
2. Midrange efficiency, η midrange = 92dB
3. Efficiency difference, η difference = 92 – 91 = 1dB, **higher for midrang**e.

Example:
To provide maximally flat midrange filter frequency response, so that:
1 Final midrange channel efficiency is the same as woofer, that is 91dB.
2 Final acoustic frequency response of midrange channel follows +/-18dB/oct Butterworth filter from 500-5000Hz for –3dB drop at the corner frequencies.

Solution:
1. Efficiency difference is nullified by inserting an L-Pad (R6+R7) attenuating signal by 1dB. Those values were calculated assuming driver's Re for the load.
2. Driver's impedance resonant peak is equalized by series notch (C8+L9+R10).
3. Driver's voice coil inductance if equalized by Zobel Network (C11+R12).

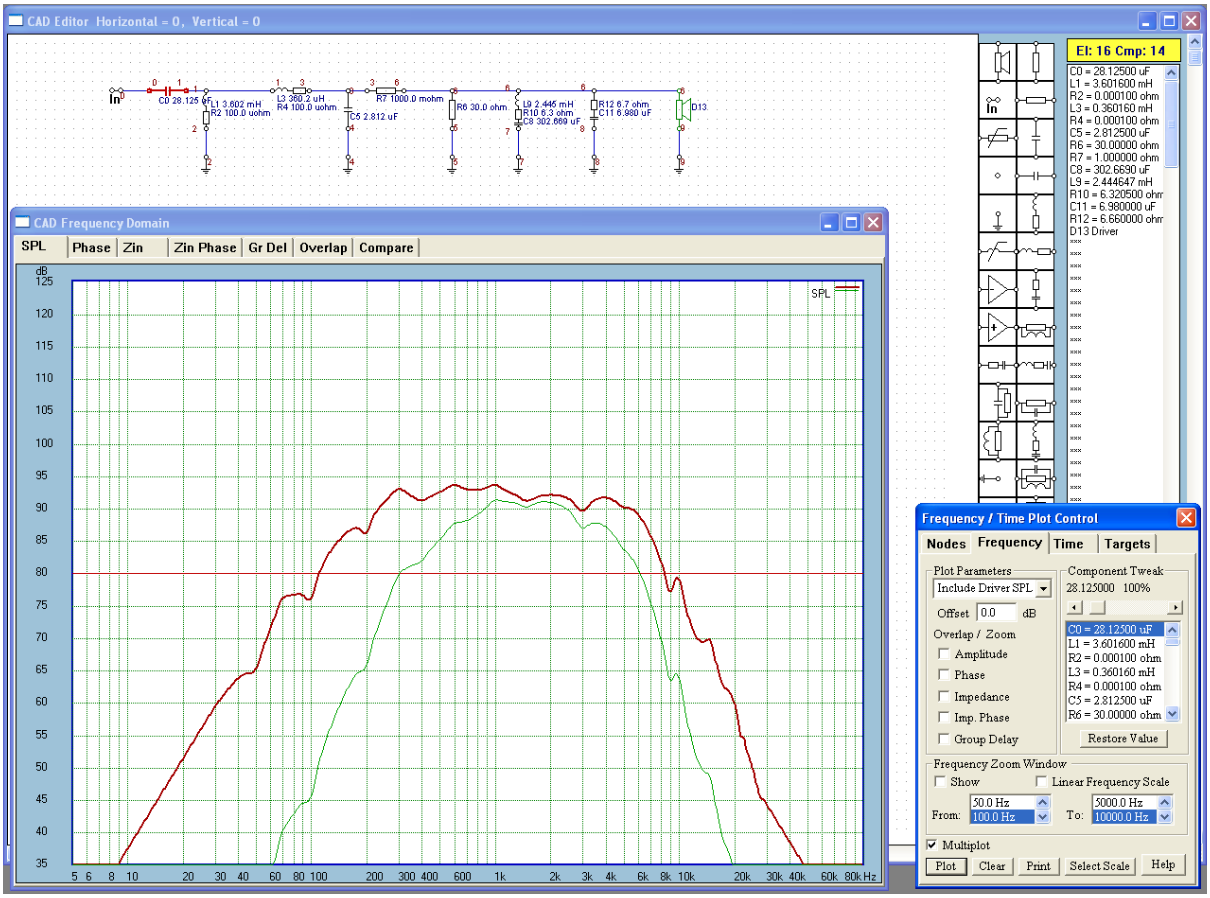


Fig 10.9 "Driver Only" – brown curve, and complete midrange filter – green curve.

Having dealt with the impedance and amplitude irregularities, we can now experiment with the Optimizer to determine if we can improve of the midrange channel frequency response. At this moment, channel frequency response is far from being optimal with the following problems:

1. Attenuation at 5000Hz is excessive, -10dB.
2. Attenuation at 500Hz is also excessive, -8dB.

The overall shape of the midrange channel acoustic response (green curve) on Fig 10.9 is far from being optimal for the selected Butterworth filter.

Excessive attenuation at 5000Hz is caused by the combination of driver's natural roll-off, which starts at 4500Hz and filter corner frequency of 5000Hz. Clearly, the combination is poorly chosen and the driver should not be used for this frequency range. However, our goal is to illustrate the design process, therefore let us see, how the optimizer would deal with this problem. We can immediately observe, that standard circuit components for Butterworth 2-nd order filter do not meet these requirements. However, driver's natural frequency roll-off will add to the steepness of the slopes below and above corner frequencies. To start the process and illustrate the procedure, we select +18/-24dB/oct reference target filter. Our initial evaluation of the problem indicated, that midrange driver's SPL was 1dB too high. The L-Pad attenuator was therefore inserted in the driver's path to reduce the level. Now, the midrange driver SPL is plotted on the screen 1dB lower (around 91dB level). However our target reference curve is still sitting on 90dB level. If nothing is done about it, the optimizer will try to compensate for this 1dB difference in levels and it is almost guaranteed, that optimized component values will be wrong.

Fig 10.10, shows the result of optimization for Attenuation = 0.0dB. Please note the Error = 434. Fig 10.11 shows the same optimization process for Attenuation = 1.0dB. The results are significantly better as Error is equal to 332. Final optimization was performed for Attenuation = 2.0dB (Fig 10.12) and the resulting Error is 346.

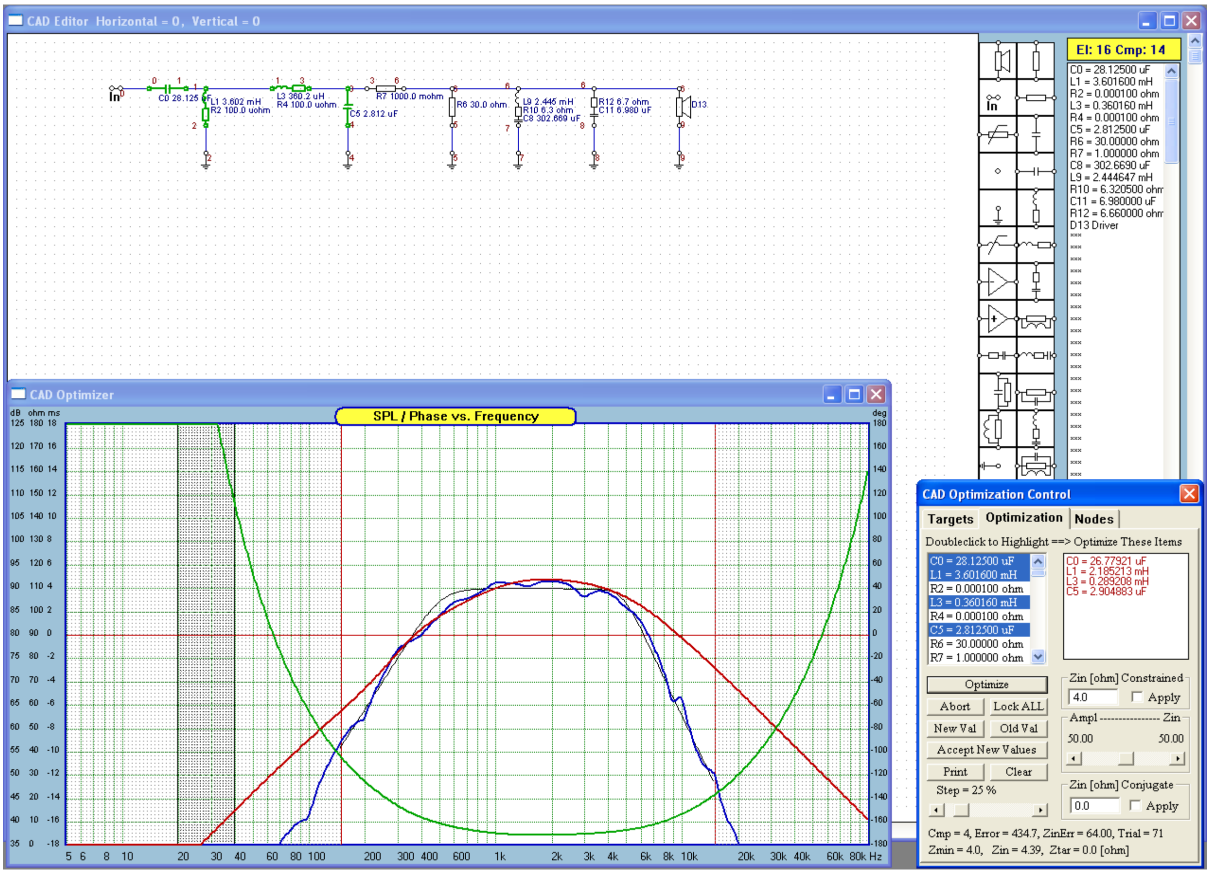


Fig 10.10. Target curve: +18/-24dB/oct, and 0.0dB attenuation. Error = 434.

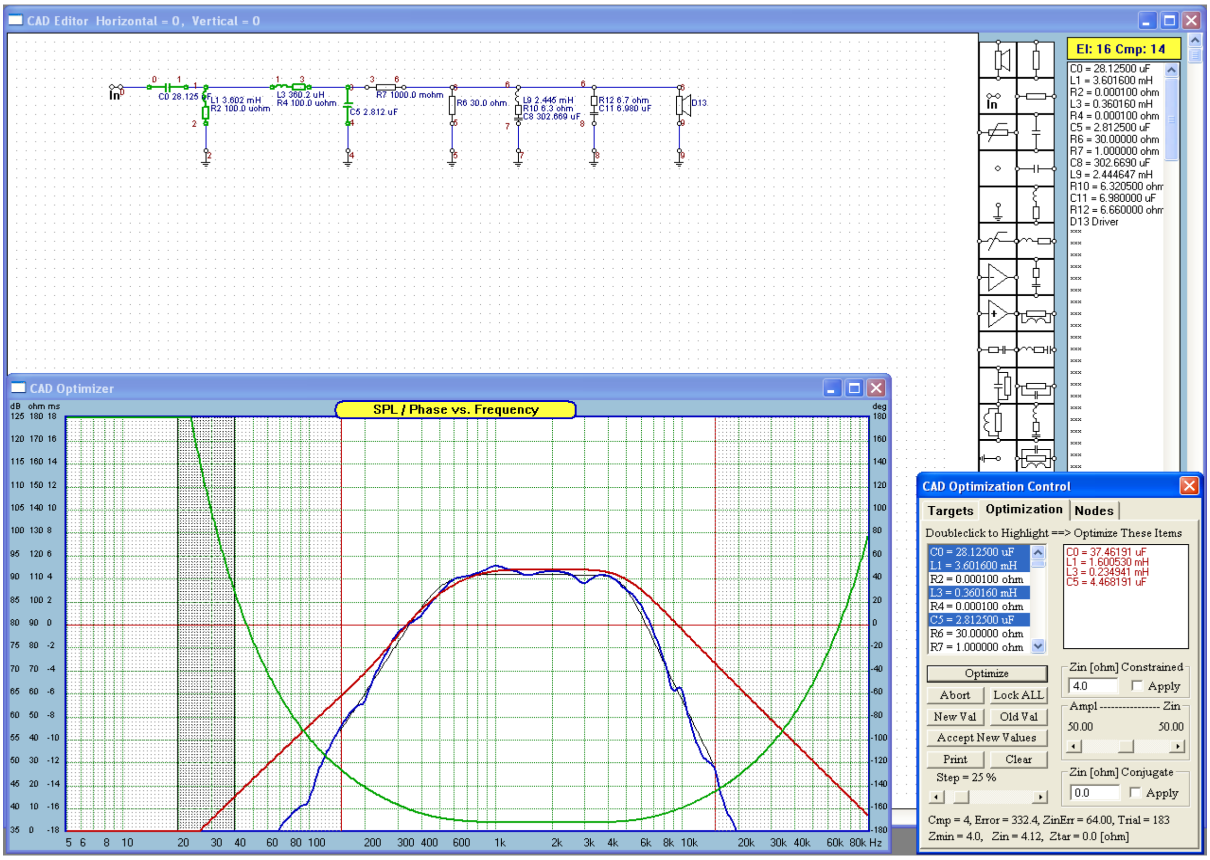


Fig 10.11. Target curve: +18/-24dB/oct, and 1.0dB attenuation. Error = 332.

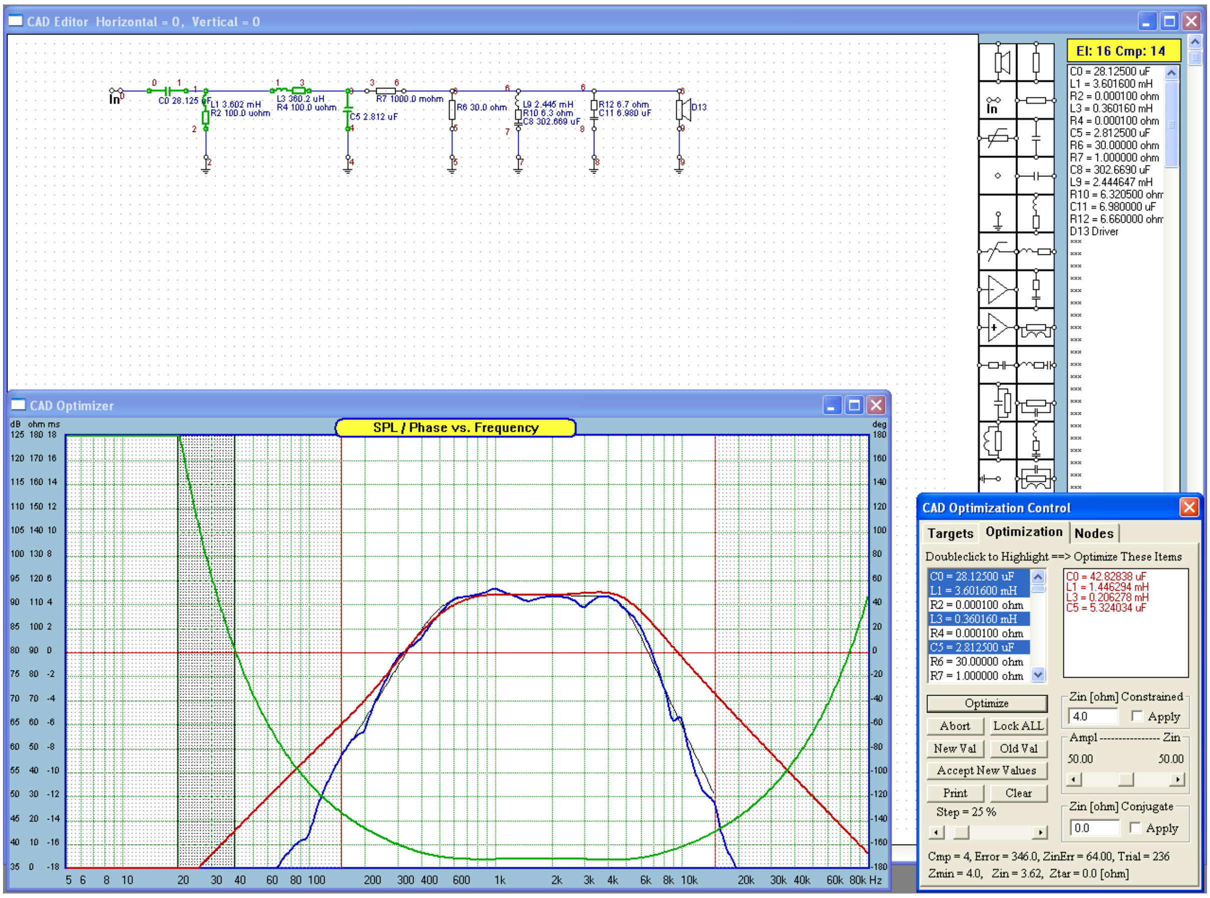


Fig 10.12. Target curve: +18/-24dB/oct, and 2.0dB attenuation. Error = 346.

The lowest Error is now 332 and it is clearly the lowest of all three optimizations. Our choice of Attenuation = 1.0dB parameter was based **on inserted L-Pad attenuation, SPL of the driver (92.5dB) and the 90dB reference the program defaults to.** In general, the whole optimization process is mathematically intensive and depends on accuracy of entered data:

1. Correctly entered (or imported) SPL curves.
2. Matching SPL curves data and SPL value. For example, if you entered 95dB for SPL of the driver, but its frequency response curve points are nowhere near this level, you have a problem.
3. Properly selected L-Pads.

It needs to be stated here, that it is quite acceptable to correct diffraction problems by reducing SPL of the midrange and tweeter drivers. In this case, you may elect to increase L-Pad attenuation, so the whole SPL curve will be shifted down by several dBs. In this case, you would need to shift accordingly the target curve for optimization, and the Attenuation field is just the way to accomplish this. As it is observable from Fig 10.10-10.12, the Optimizer also decided to shift the upper slope of the filter to about –12dB/oct. This is due to the unfortunate choice of the driver/filter combination, where driver alone rolls-off too early and quite steeply. Other component values were adjusted for the "best fit" to the targeted +18/-24dB/oct target response.

To visualize the results of the optimization, the original midrange response and the optimized midrange response were plotted on Fig 10.13 and 10.14 respectively. It can be easily observed, that the optimized curve is significantly better match to the required Butterworth, 3-rd/4-th order bandpass filter with 500 – 5000Hz corner frequencies and efficiency of 91dB.

Interestingly, the improvement in performance was accomplished without changing the topology of the filter. The asymmetrical filter was selected as an example only, but please observe, that the original frequency response of the midrange driver (Fig 10.9) also exhibits asymmetrical character.

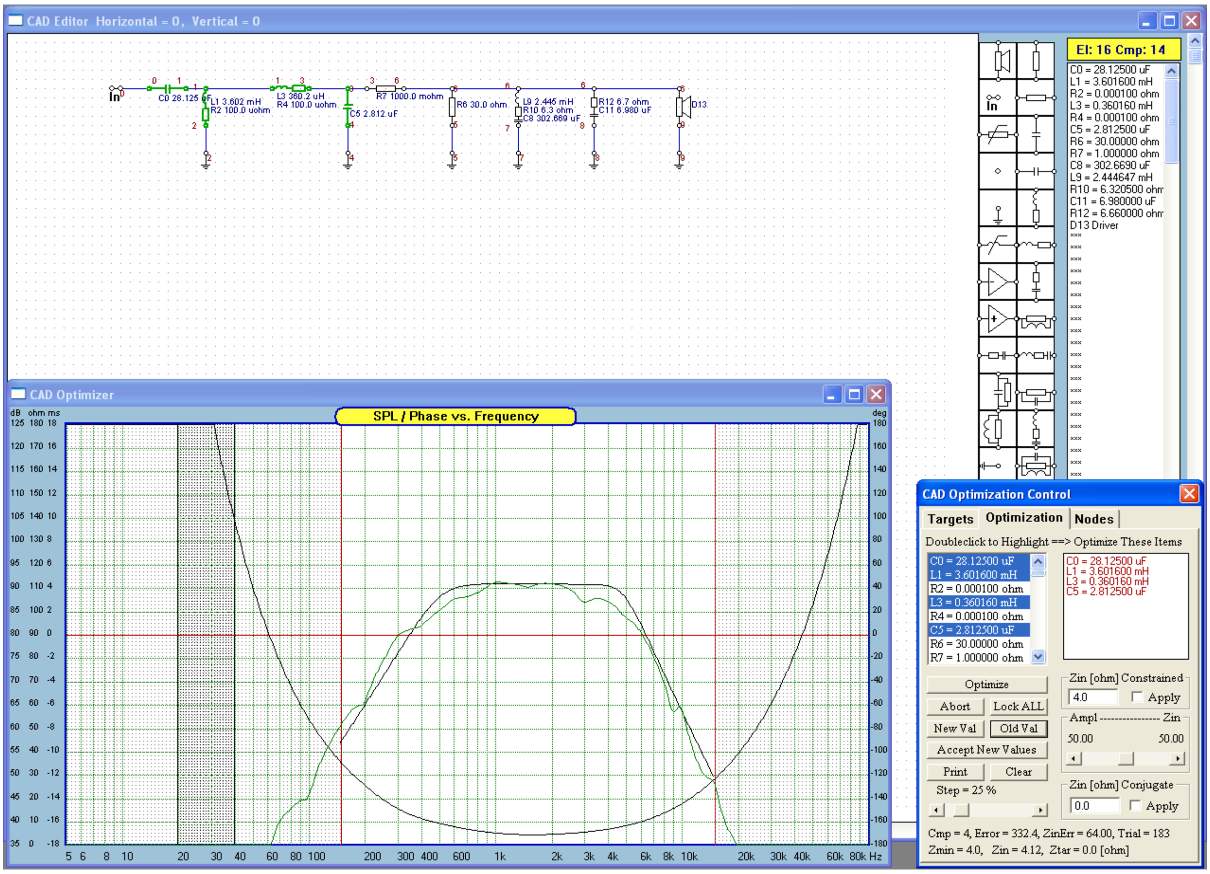


Fig 10.13 Original midrange filter – curve 1, +18/-24dB/oct target – green curve.

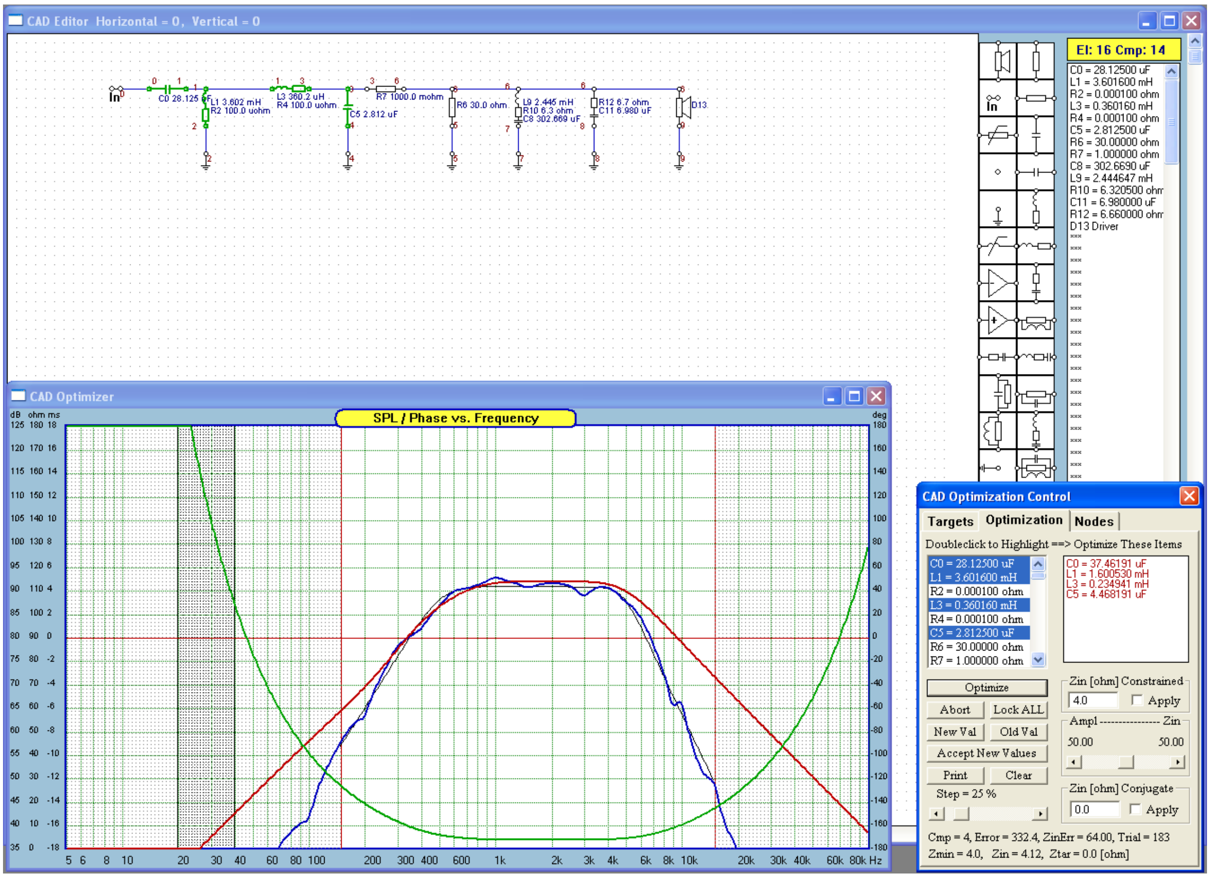


Fig 10.14 Optimized midrange filter – curve 1, +18/-24dB/oct target – blue curve.

In summary – please refer to Figure 10.15

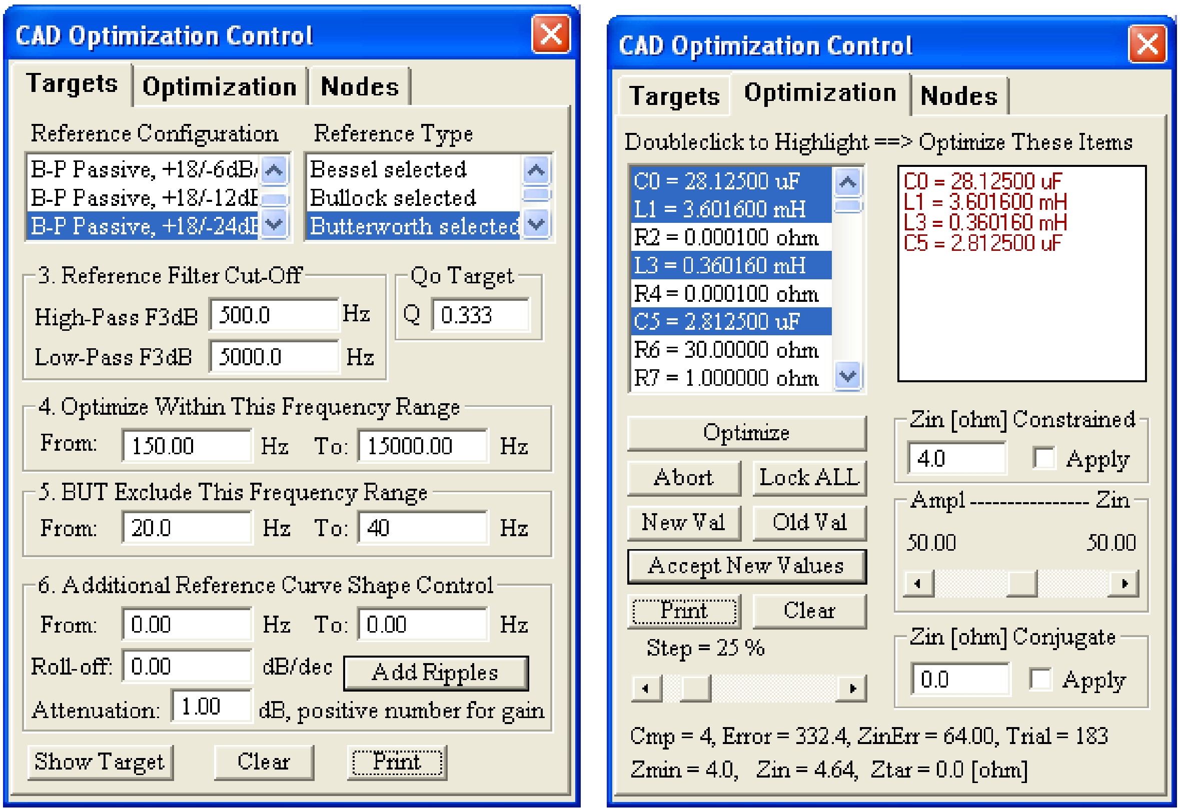


Figure 10.15. Optimization Controls.

Optimization process is intended to adjust crossover components, so that the overall acoustical response of the channel (woofer, midrange and so on…) is close to the ideal electrical filter response. **Optimization Control Dialogue Box** has the following controls:

Targets Tab

1. Select the required Filter Configuration from the **"Reference Configuration**" list box.
2. Select the filter (eg: Butterworth) type from the "**Reference Type**" list box.
3. **"Reference Filter Cut-Off**" – High-pass and Low-pass frequencies of the filter.
4. **"Optimize Within This Frequency Range"** - two editable fields to accomplish just that. Enter frequencies in Hz.
5. **"BUT Exclude This Frequency Range"** – again, two editable fields to accomplish just that. Enter frequencies in Hz.
6. **"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.
7. 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.
8. It is recommended, to use **"Show Target"** button on the dialogue box to review system target reference line before commencing optimization process.
9. **"Clear"** button – simply clears the screen.
10. **"Add Ripples"** – this button closes the "Optimization Control" box and opens another box to enable you to add 3 ripples.
11. **"Print"** button – prints the screen.

Optimizer Tab

1. **"Lock All"** button – press to lock out all components from optimization.
2. **"New Values"** button – press this button if you are happy with the optimized values and you want to use them across the module.
3. **"Old Values"** button – press this button if you want to return to the original component values.

4. **“Accept New Values”** – press this button to accept newly optimized values.
5. **“Clear”** button – simply clears the screen.
6. **“Abort”** button – press this button to STOP optimization process.
7. **“Optimize” –** pressing this button invokes the “Optimization Control” dialogue box.
8. **“Print”** button – prints the screen.
9. **Zin [ohm] Constr -** editable data field to enter the lowest acceptable input impedance your amplifier can tolerate. **MUST be greater than 0.1ohm**
10. **Zin [ohm] Constr - “Apply”**: checkbox to enable/disable Zin restriction.
11. **Zin [ohm] Conjugate -** editable data field to enter the lowest acceptable input impedance your amplifier can tolerate. **MUST be greater than 0.1ohm**
12. **Zin [ohm] Conjugate - “Apply”** – checkbox to enable/disable Phase restriction.
13. **“Amplitude ----- Zin”** - use this slider to apportion mutual importance level to 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.
15. Nodes TAB is the same as described in CAD section of this manual.

<u>Please note, that SPL optimization is achieved by un-checking **Zin [ohm] Constr - “Apply”** checkbox, and un-checking **Zin [ohm] Conjugate - “Apply”** checkbox.</u>

Constrained Optimization

At times, you may need to assure, that the best optimization process does not lead to the resulting input impedance dropping dangerously low – that may cause potential problems for the power amplifier. If you feel, you need to keep minimum input impedance of the system or crossover around some predetermined value, please enter this value in the provided **Zin [ohm] Constr** data field. The results of the optimization will typically be not as good as for “unconstrained optimization”. An example of two types of optimization are given on Figure 10.16 and Figure 10.17. Firstly, constrained optimization was performed on the midrange filter and the requested minimum input impedance was set to 5.0 ohm. Next, unconstrained optimization was performed. The result was the Error was much lower for the unconstrained optimization. However, both results were a significant improvement over the original SPL curve.

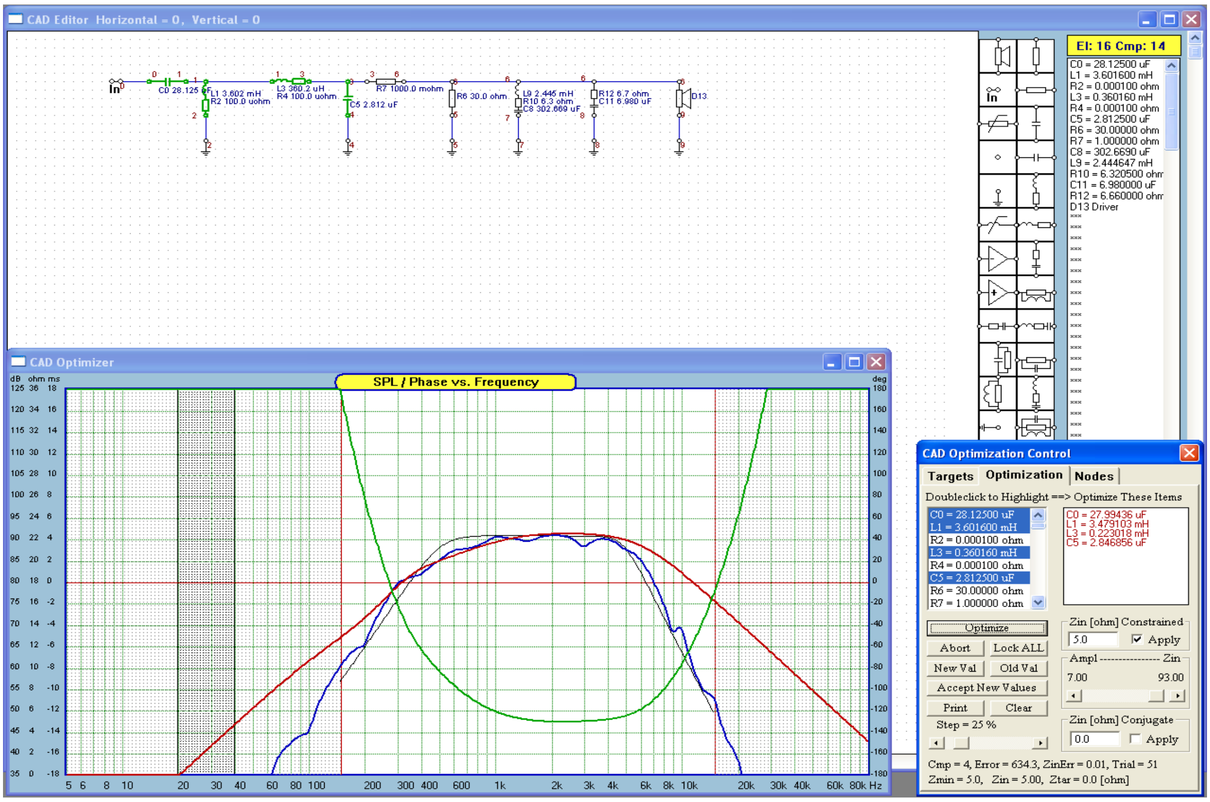


Figure 10.16. Results of constrained optimization – Error = 634. Zin = 5.0ohm.

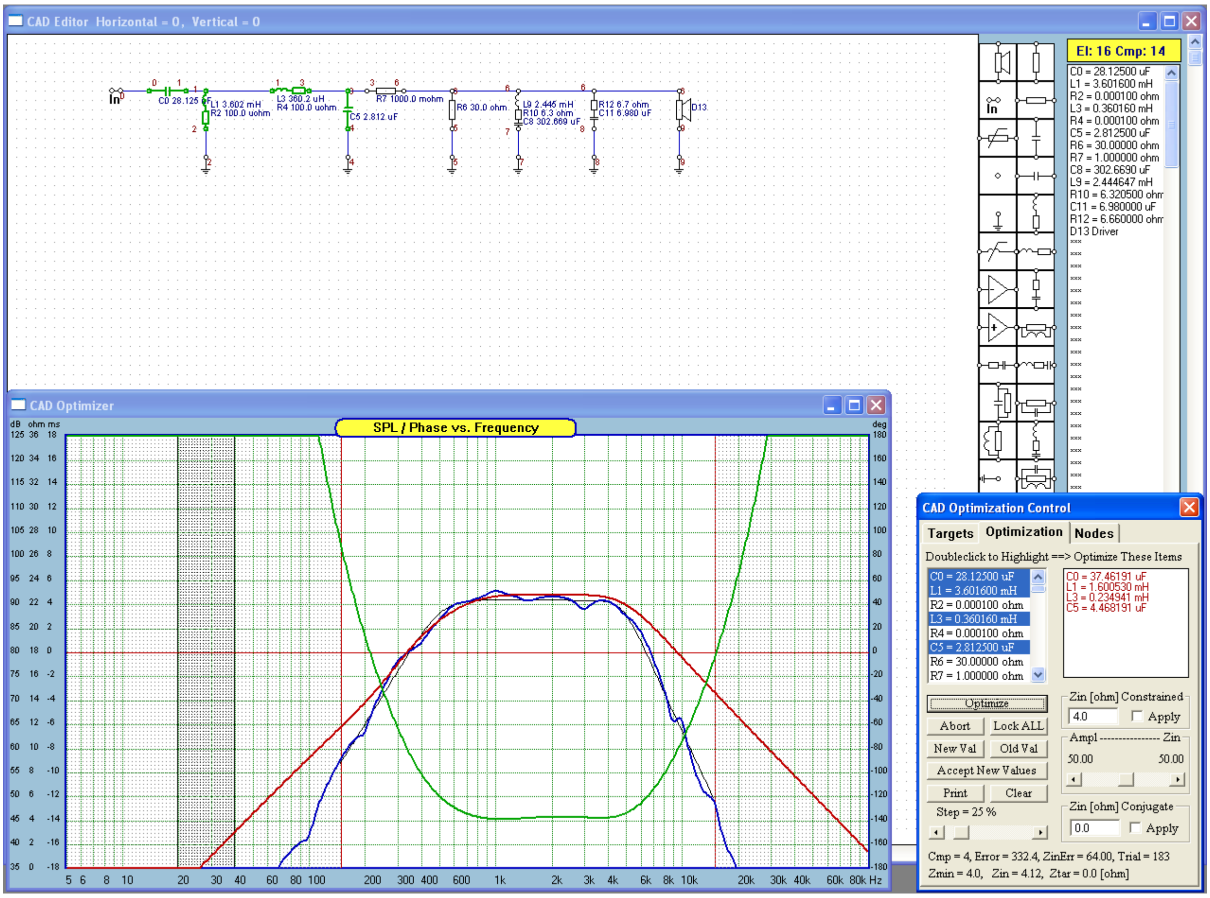


Figure 10.17. Results of unconstrained optimization – Error = 332, Zin = 4.12ohm.

User Defined Complex Target Curves

When running the Optimizer process, you may at times desire to use pre-defined target SPL curves. SoundEasy provides you with a means to generate practically any target SPL curve using the Editor Screen. Any curve plotted on the Editor Screen can be used as the SPL target curve in the Optimizer process. At the end of the editing process, you will be able to save the newly created curve as ASCII file, containing all 750 data SPL points. This file can be further edited, if desired.

You may decide to create the entire target SPL curve using one of the available text editor programs as well, and then simply import it into SoundEasy Optimizer screen. In this case, we suggest you make your life easier by making an ASCII "template" of the target file. Simply start SoundEasy and select "Import/Export Data" -> "Export SPL/Phase at 0.0dB" while the program is in the default stage. This will create complete ".trg" file with 750 data points, showing the frequency column data and all SPL entries equal to 0. The frequency data points are already there for you, so this file can now be quickly edited for the desired SPL data using the external text editor.

In order to create the target SPL curve, we recommend you should start with the "Driver Parameter Editor" -> "Amplitude Model" tab, to start editing process for the target SPL. The process is identical to editing the SPL curve of a driver and has been described before. Figure 10.18 below shows the target SPL curve created using "Amplitude Model" tab (to get the initial shape of the curve). You can hand-draw (add) distortions after that.manually on the Editor Screen using the mouse pointer. This illustrates the possibility, that you can edit every single pixel on the Editor Screen.

The process of editing the target SPL curve is entirely graphical. For "fine tuning" the curve, you should "click" the left mouse button over the thick, pink SPL curve – this will activate small gray-colored screen cursor and then you can use cursor keys to move the screen cursor , at the same time re-drawing the SPL curve.

Finally, you must create Transfer Function from the edited template using HBT TAB – see Figure 10.19. This process will create Frequency – SPL – Phase columns in your target file. Now, the target file is ready to be used in the Optimizer process.

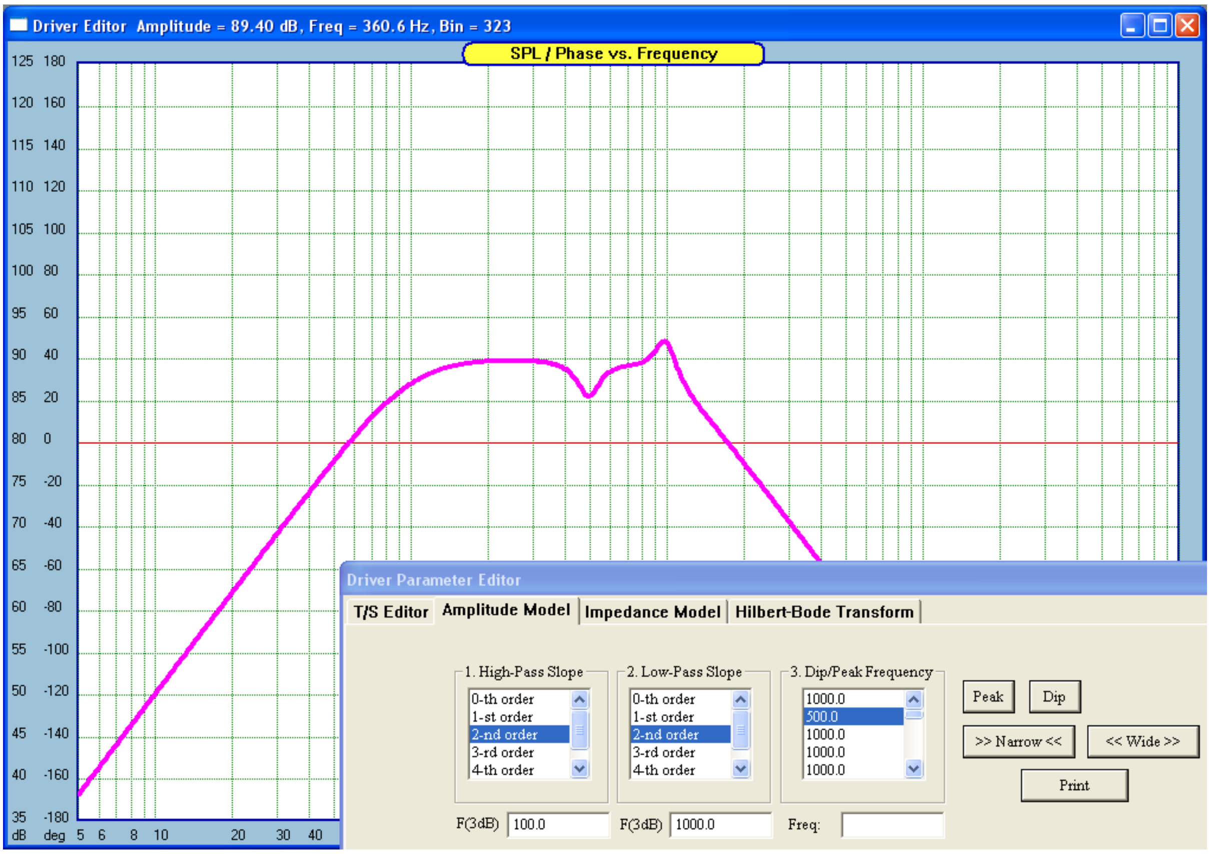


Figure 10.18. Editing SPL target curve using Editor Screen.

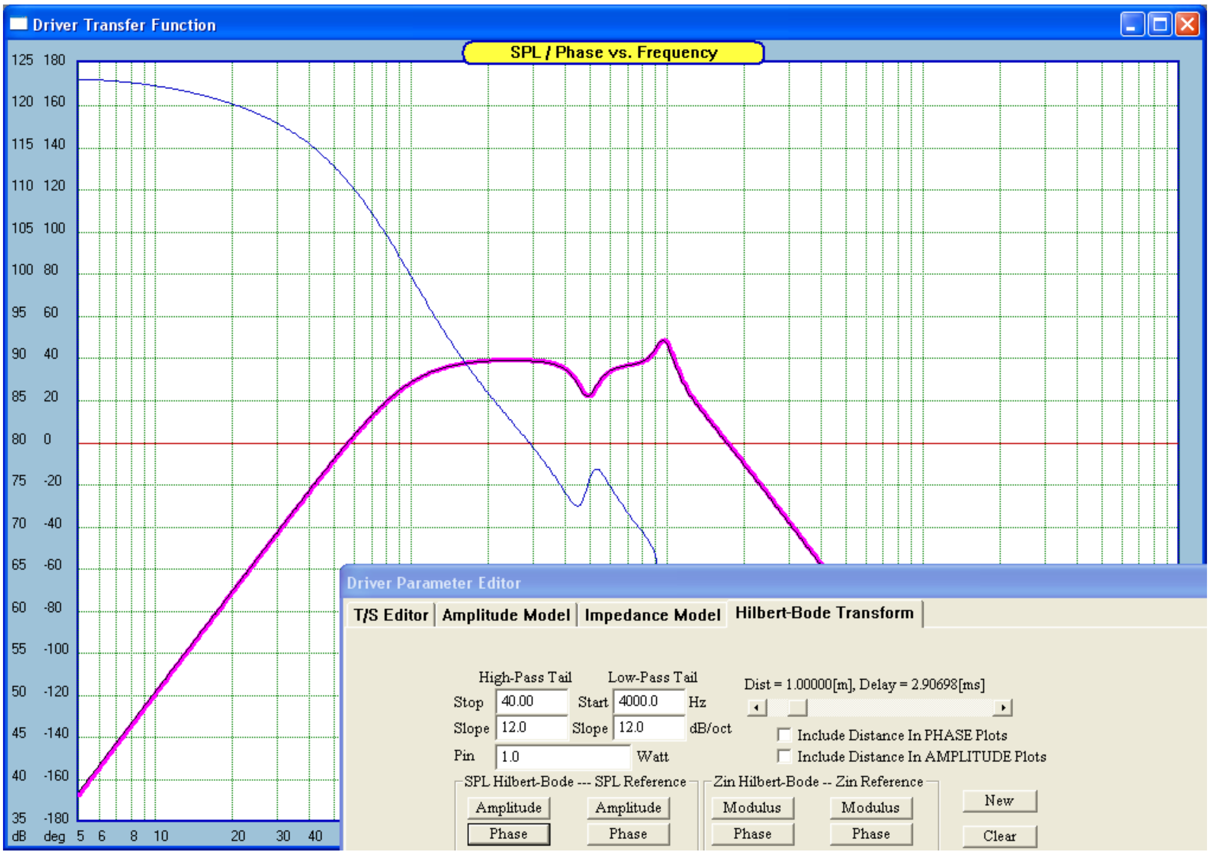


Figure 10.19. Converting edited SPL target curve to Transfer Function, using HBT function.

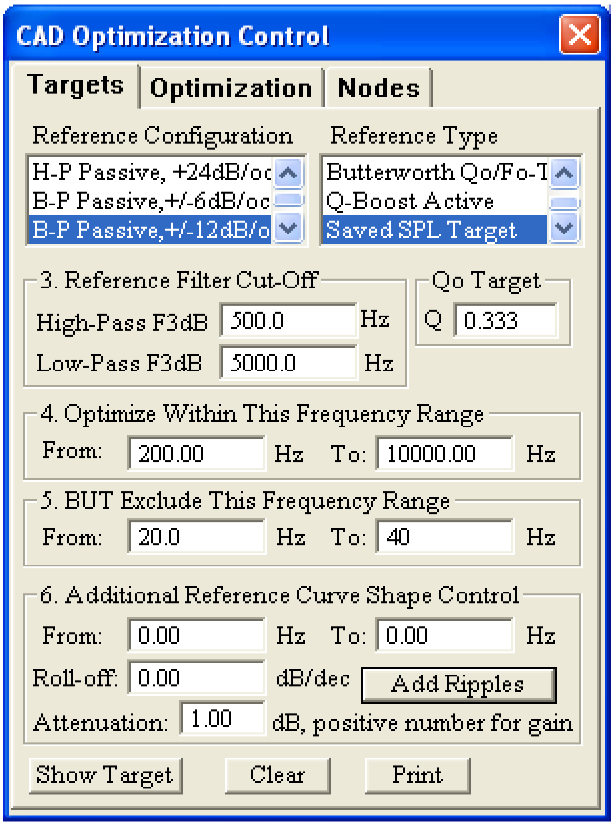


Figure 10.17. Selecting ".trg" file for target

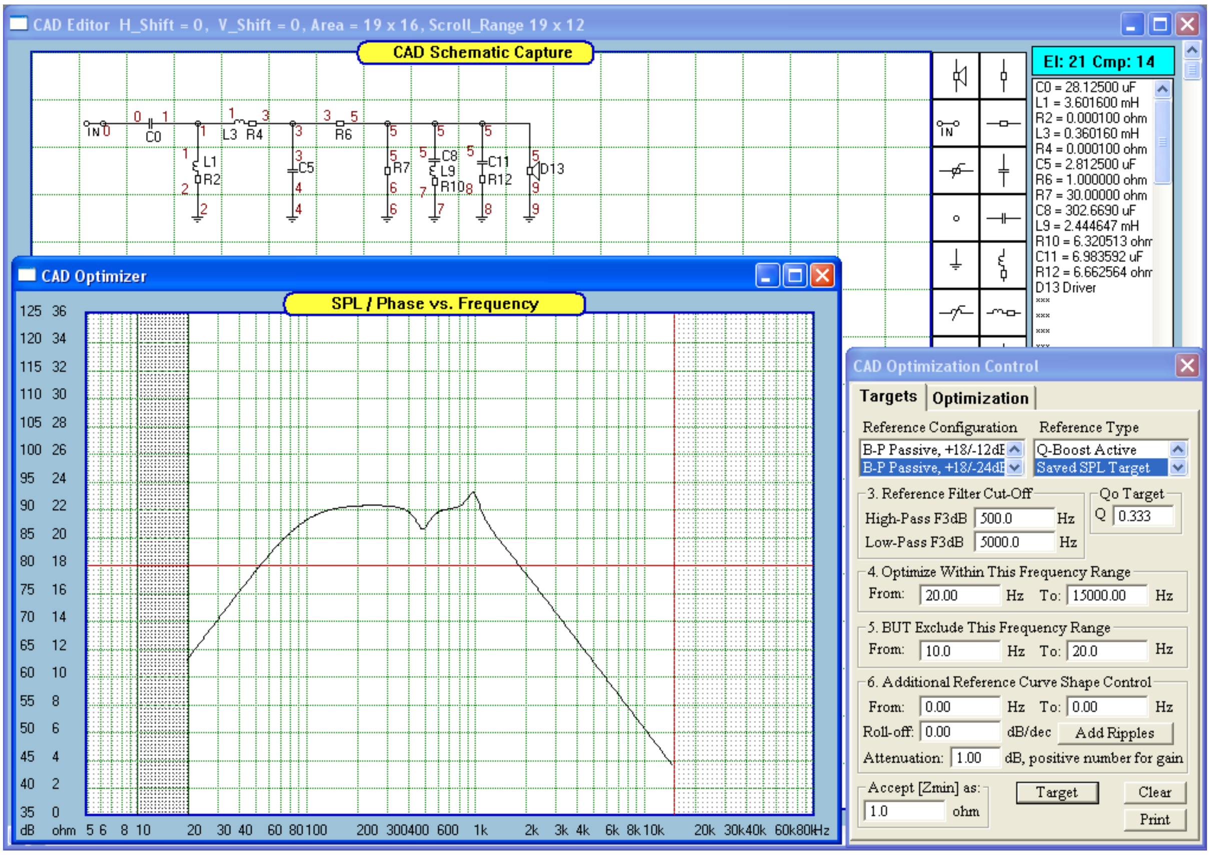


Figure 10.18. Target SPL curve

Conjugate Impedance Optimizer

Compensating driver's input impedance due to the semi-inductance of the voice coil, can be assisted by using Conjugate Impedance Optimizer. The Conjugate Impedance Optimizer function is primarily designed to work for Zobel networks, but you may be able to use it for other circuits as well. **The Conjugate Impedance Optimizer always attempts to adjust selected circuit elements, so that the input impedance into this circuit is a flat line (constant resistance), centered around Zin Conjugate data**.

Optimization results can be generally sensitive to selecting initial values of the components, optimization parameters and optimization frequency range.

The frequency range of optimization was selected to start above minimum impedance point for a "raw" impedance curve. In our example, it is deemed to be 300Hz. Frequencies below this point, should be EXCLUDED from optimization. The upper bound of the optimization frequency range should be the screen limit (100kHz in our example).

As for typical optimization requirements, you need to LOCK/OPTIMIZE appropriate components. In our example, both, C0, R1 are being optimized – see Figure 10.19. To start Conjugate Impedance Optimizer function, please check **Zin [ohm] Conjugate - "Apply"** box and press **"Optimize"** on Optimization TAB.

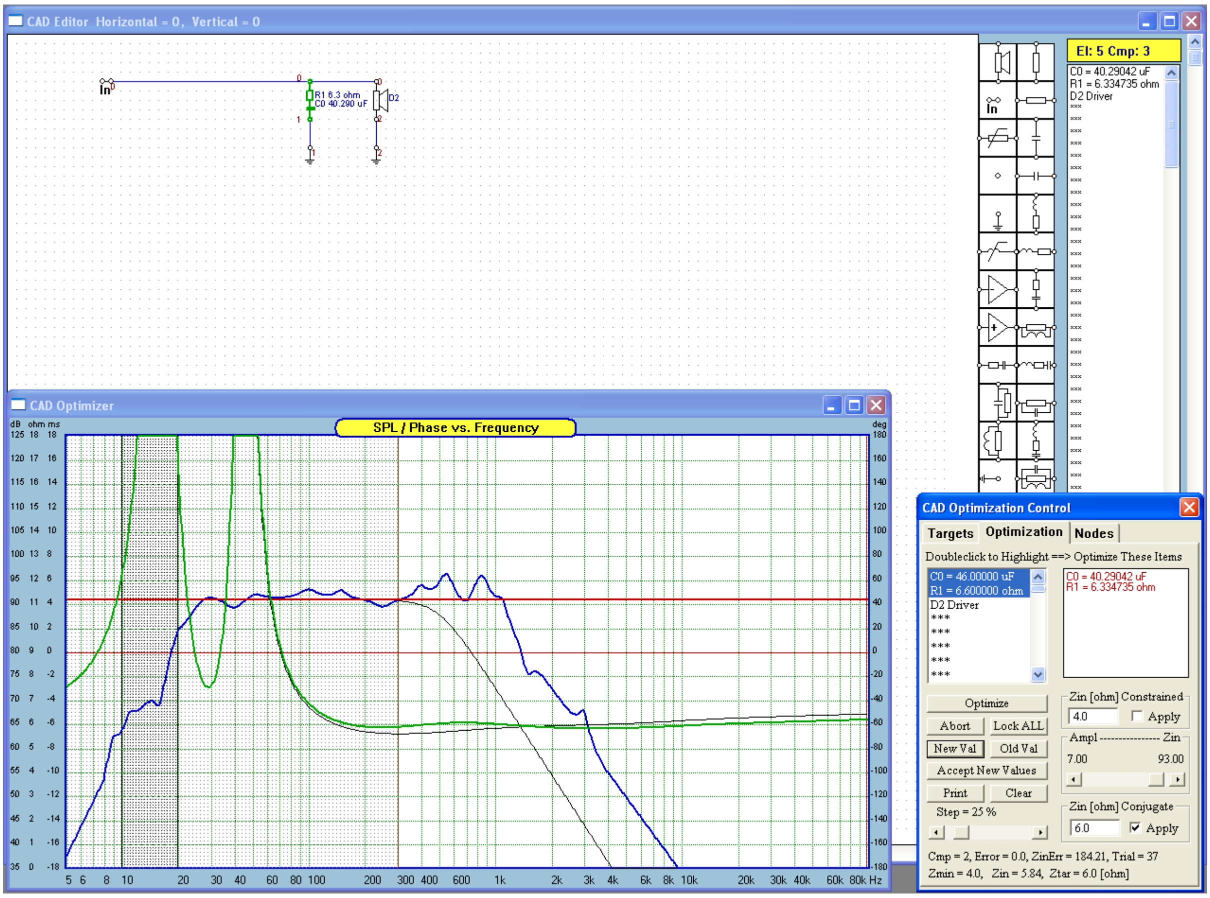


Figure 10.19 Basic schematic and highlighted Zobel network for input impedance compensation.

It is suggested, that for typical 12" woofer, with Re=6.0ohm, you may stat with initial Zobel values of R1 = 6.6ohm, C0 = 46uF – see Figure 10.19 above. **Zmin** (minimum allowed impedance) should be set around the Re value, so it was set to 6.0ohm, and **"Apply"** box checked to activate it.

After optimization, R1 = 6.3ohm, and C0 = 40.2uF. The green curve on Figure 10.19 shows the flattened improvement in Zin.

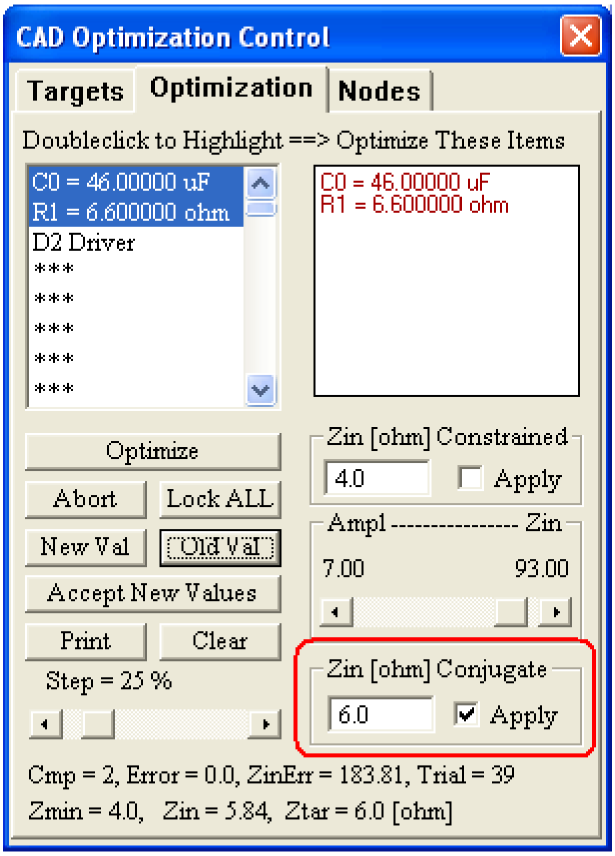
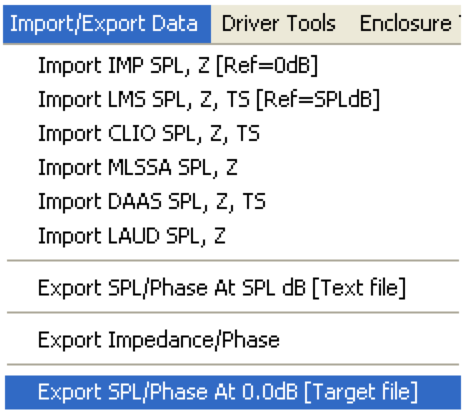


Figure 10.20 Location of controls for the Conjugate Impedance Optimizer.

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.

Crossover Design and Optimization Using Off-Axis Curves

On-axis, as well off-axis SPL/Phase measurement curves are available for crossover design and optimization. The optimization process assumes, that all necessary off-axis measurements have been recorded for the selected drivers. In addition, off-axis optimization should be performed for identical angles selected from "Polar" column for all drivers involved.

The example below shows woofer and tweeter drivers selected for crossover design using +50deg off-axis SPL/Phase frequency responses.

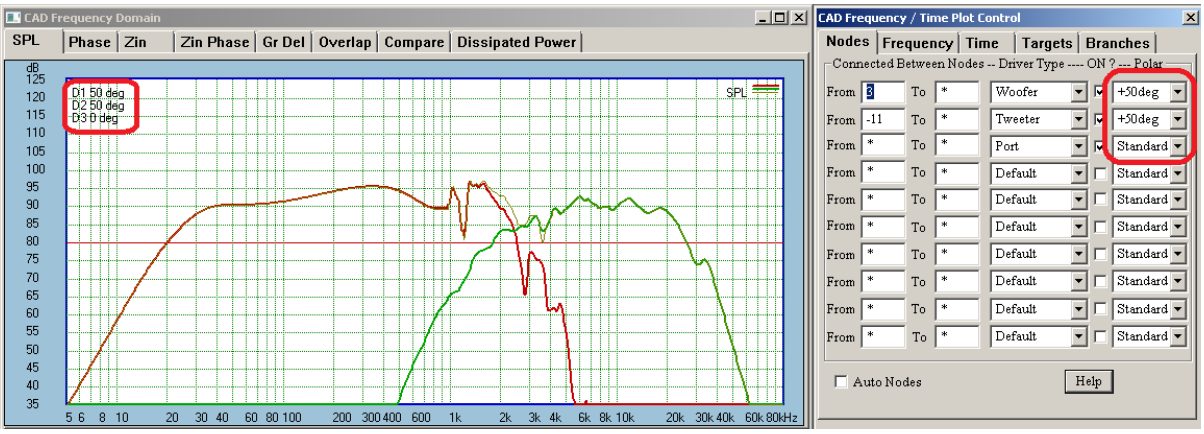
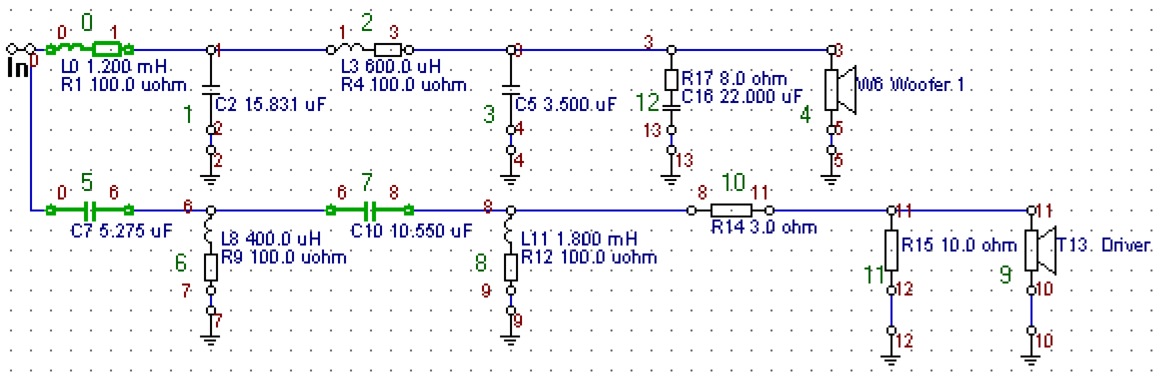


Figure 10.21. Selecting 50deg off-axis SPL curves for crossover optimization.

The example below shows woofer and tweeter crossover components selected for crossover optimization using +50deg off-axis SPL/Phase frequency responses.



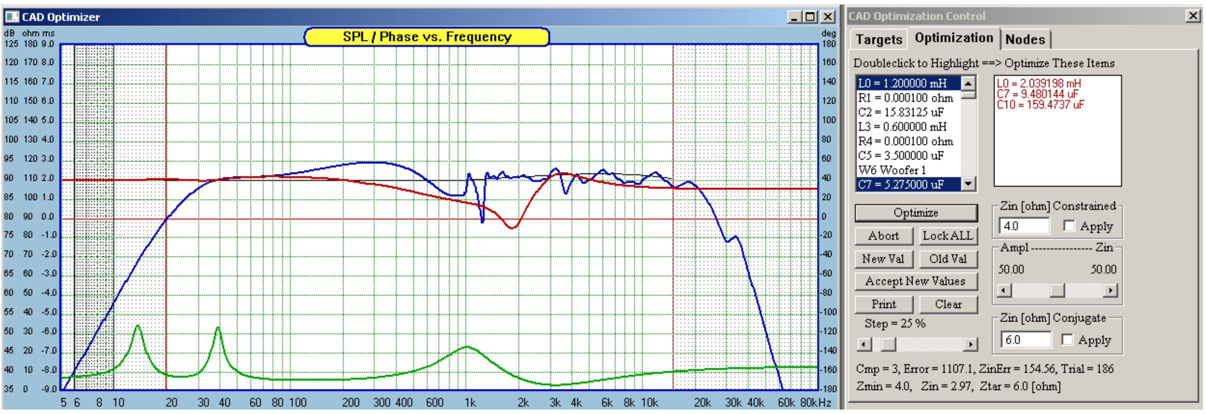


Figure 10.22. Crossover component selected for optimization.

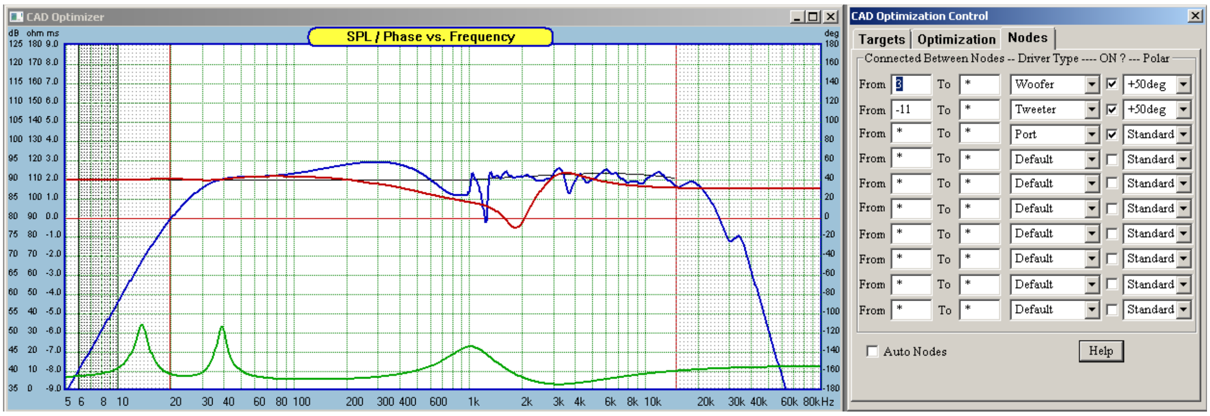


Figure 10.23. Setting Nodes.