Chapter 11. Crossover in Time Domain

Background

Over the past decade there has been growing recognition of the importance of loudspeaker transient performance. Accurate transient reproduction ability has been associated with phase response of the system. Voltage transients, when transformed into the frequency domain, are characterised by the presence of a rich array of frequency components simultaneously, which are related to each other with correct phase. When the phase relationship between these components is distorted during the reproduction, the resulting transients are also affected. Amplitude response alone is no longer sufficient to evaluate quality of the design and assure the user, that all forms of audible distortion have been compensated.

Rather than displaying phase response and drawing conclusions from it, a better test is being proposed. A step function, or square wave is being fed into the system and the time response to this excitation recorded. You may recall from Chapter 6, that square wave is composed from many individual sine waves, having specific phase relationship. It is obvious, that if the system under test, disturbs the existing phase relationship in the test signal, then the sine wave components will not add correctly after passing through the system and the resulting output will no longer resemble a square wave. A good point to start evaluating the transient response is the crossover. This is an area, where the designer has some degree of freedom in selecting the configuration and component values of the filters. The 'Time response' function module operates on the crossover section of the data file. However, it can be used as a "free standing" module for testing new ideas or circuit configurations - without saving the results of your work. Another area of concern is the difference in the acoustic path length from the acoustic centre of each driver to the listener. This problem can be studied in details using the "System" tools.

There are several methods being used in analysing electrical circuits in time. The 'Crossover' tool offers two methods: (1) Fast Fourier Transform (FFT) and (2) Matrix Nodal Method. For the first method, the basic idea of "How it is done" was explained in the previous chapter, so it is sufficient to state, that "Crossover" tool also uses Convolution in Time method to obtain time response of the analysed circuit. The Nodal Method will be explained in more details in the remainder of this chapter. Evaluating channel response in frequency domain only, offers the designer only a limited insight into the quality of the design. As it will be shown later, crossover filters, which display only a small ripple in the summing region, do not add voltages correctly in the time domain. As a matter, of fact, most passive crossovers don't. Those which do, are called "Constant Voltage" crossovers (Small, JAES, January, 1971, Vol 19, Number 1). The analysis can be performed in two modes explained below. Extensive menu offers the user several options for plotting and saving the curves in the provided buffers. Time Domain analysis window can be opened from the main menu.

Time Response Menu

There are several options available to the user from the floating menu of the FFT screen. The options are explained below:

1. **Standard Mode -** to be used with the files or circuits, that include drivers and their frequency responses.

* Calculates the network transfer function for FFT fundamental frequency (selected from the editable window - Test Frequency) and harmonics up to 40kHz.
* Calculates FFT of the square wave.
* Calculates the product of the above (Convolution).
* Calculates IFFT and plots the result on the screen (time response).
* The curve is saved in the buffer.

2. **Extended Mode -** to be used with the files or circuits, that DO NOT include drivers and their frequency responses.

* Calculates the network transfer function for ALL FFT harmonics.
* Calculates FFT of the square wave.
* Calculates the product of the above (Convolution).
* Calculates IFFT and plots the result on the screen (time response).
* Saves the curve in the buffer in the first available location.

Time Tab

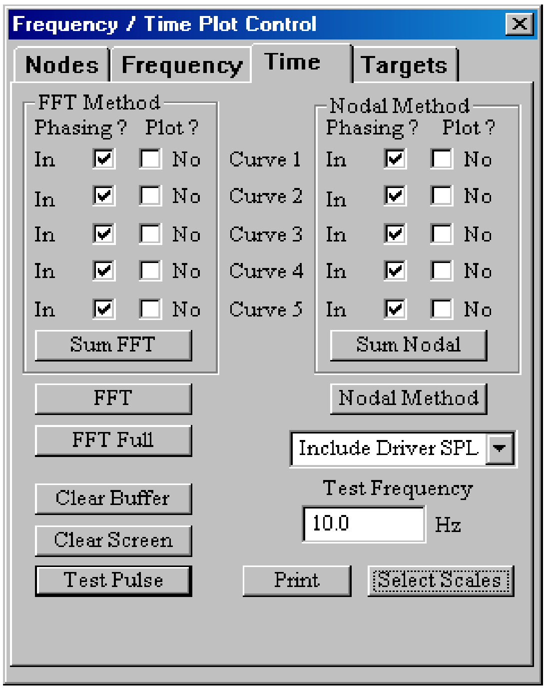

Figure 11.1. Tab for controlling Time-Domain plots

1. **FFT Method combobox –**
2. **Phasing ?** check-box column – "In" phase indicates no phase reversal. "Out" of phase indicates
3. phase reversed by 180 degrees.
4. **Plot ?** check-box column – "No" indicates do no plot this curve. "Yes" indicates inclusion of the curve in plots.
5. **Sum FFT button –** Plots summed response using FFT method
6. **Nodal Method combobox –**
7. **Phasing ?** check-box column – "In" phase indicates no phase reversal. "Out" of phase indicates phase reversed by 180 degrees.
8. **Plot ?** check-box column – "No" indicates do no plot this curve. "Yes" indicates inclusion of the curve in plots.
9. **Sum Nodal button** – Plots summed response using MNM method
10. **FFT button** - Plots summed response using FFT method. You **can include driver icon in the CAD** schematic when plotting time domain response using this method.
11. **FFT Full button** - Plots summed response using FFT method. You **<u>must not</u> include driver icon in the CAD** schematic when plotting time domain response using this method.
12. **Clear Buffer button** – Clears memory storage allocated for 5 curves.
13. **Clear Screen button** – Simply clears the screen.
14. **Test Pulse button** – Plots the test pulse.
15. **Test Frequency editable field** – Enter your test frequency here.
16. **Drop-down list** box for selecting additional plotting parameters.
17. **Print button** – Invokes printer dialogue box.
18. **Select Scales** – Button opens dialogue box for selecting vertical scale resolution.

Standard Mode vs. Extended Frequency Mode

Individual time response of every frequency channel may reveal additional useful information. Area of particular importance however, is the "crossover" range of frequencies. This module adds up to five time responses, in- or out- of phase, stored previously in Standard or Extended Frequency Mode. The Standard Mode should be used when plotting time response of any circuit developed with the help of other SoundEasy modules. As it was explained in Chapter 1, the program operates within 1 - 100000Hz frequency range. You may still decide to use Extended Frequency Mode, but the plotted time responses will have reduced accuracy for higher sampling frequencies (frequency of the square wave) - see Fig 11.3. For example: let's assume, that sampling frequency was selected as 20 kHz.

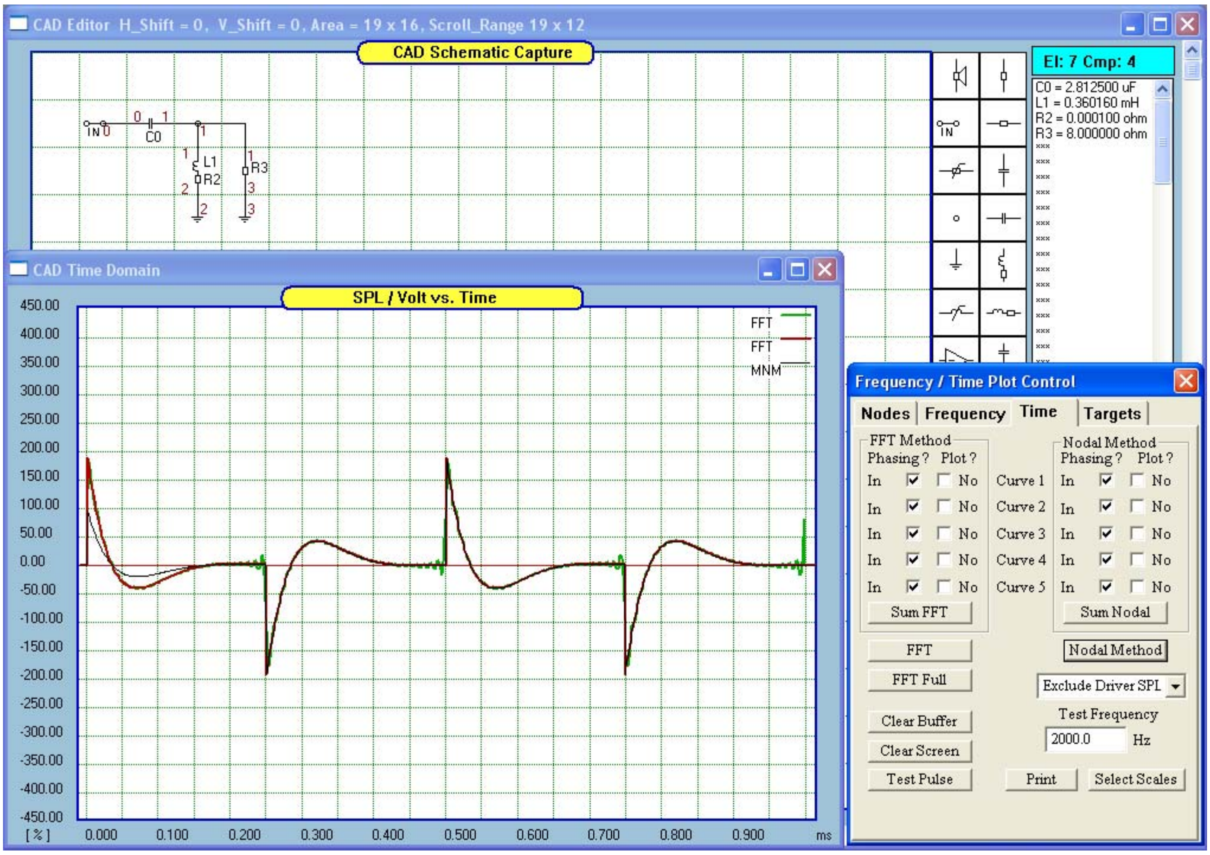

Fig 11.2 Three options for obtaining time plots: FFT – green, Full FFT – brown, MNM black.

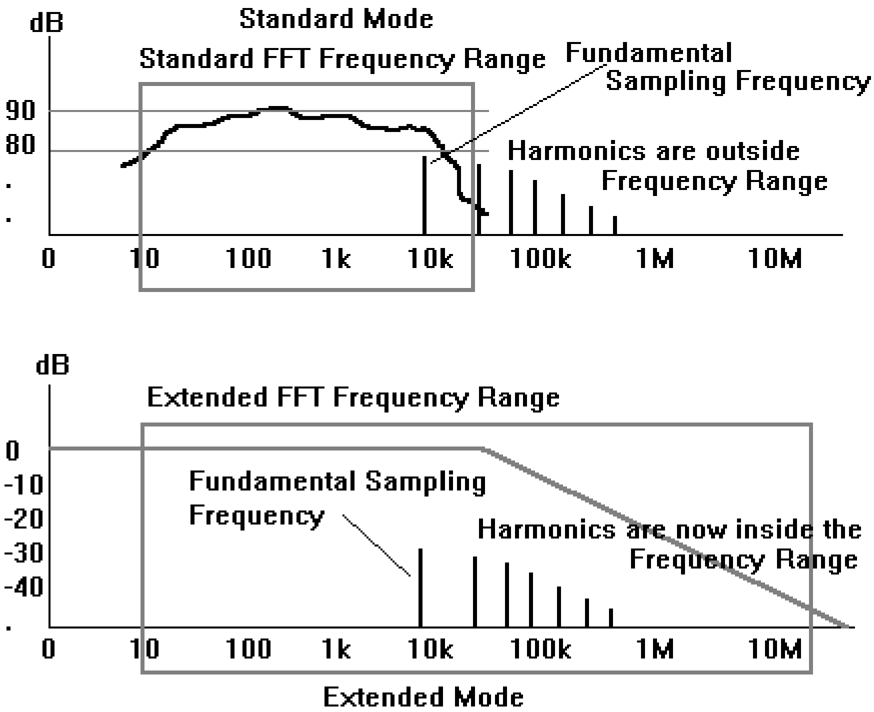

Fig 11.3

The first odd, non-zero harmonic (F2) of the square wave will be 60 kHz. The next non-zero harmonic (F3) will be 100kHz and so on. All the harmonics, F2, F3 and higher fall outside the 10 - 40000Hz frequency range where the frequency response of the proposed circuit is not calculated (it is actually assumed to be zero). As a result of this, the higher harmonics of the FFT process can not contribute to the final result of the Convolution in Frequency and the error is produced. The size of the error can be estimated from the Fig 11.2. The figure shows two time response plots of the same circuit. The curve labelled "0" was plotted in Standard Mode and it can be observed, that the curve has a few "waves" on it. The result of missing harmonics was explained in the previous chapter, when the process of building a perfect square wave was explored. The second curve, labelled "1" was obtained in the Extended Mode. The Standard Mode will yield good results below 1 kHz sampling frequency and will offer reasonable approximation up to 5 - 6 kHz. This should be sufficient for most of the midrange-tweeter crossover points used in three-way systems. In the Extended Mode, SoundEasy is able to calculate and add all 1024 (or rather 512 odd) harmonics and produce accurate results. This mode is recommended for all study and analysis of CAD circuits (but remember, the circuit must not contain loudspeaker symbol or "Include Driver" mode).

Nodal Method - How it is done ?.

The circuit you have designed is analysed by Nodal Method using complex number matrixes. In the frequency or time domain the process broadly follows the steps described below.

1. The designer creates the circuit using CAD methods described in the previous chapters.
2. All necessary information about the circuit is stored in a large matrix, which will later be used as a circuit reference.
3. Based on (2), incidence matrix Aa[][], relating to passive elements and Ab[][], relating to active elements are created.
4. Datum node (rows corresponding to ground connections) are then removed from the Aa[][] matrix.
5. The Aa[][] matrix is then transposed to $Aa^T[][]$ and Ab[][] is transposed to $Ab^T[][]$.
6. Complex branch conductance matrix Ga[][] for passive components is formulated next.
7. Complex branch conductance matrix Gb[][] and branch resistance matrix Rb[][] for active components are formulated next.
8. Independent complex branch current vector J[] is formulated.
9. Matrix Rb[][] is inverted to $Rb^{-1}[][]$.
10. Complex nodal conductance matrix Gn[][] = Ga[][] - Ab[][]*$Rb^{-1}[][]$*Gb[][]*$Ab^T[][]$.
11. Now, algorithm enters the main loop and calculates circuit response for individual frequencies or time steps.
11.1 Nodal current source vector Jn[]=A[][]*J[].
11.2 Nodal voltage vector Vn[]=-Jn[]/Gn[][]. At this stage, inversion of matrix Gn[][] is performed.
11.3 Branch voltage vector V[]=$A^T[][]$*Vn[].
11.4 Passive branch current vector Ia[]=Ga[][]*$Aa^T[][]$*Vn[].
11.5 In the time domain, the algorithm now solves first order differential equations for simple components and integro-differential equations for compound (LRC) components. Second-order Runge-Kutta method was implemented.

In the time domain, the algorithm advances a small fraction of a second at a time. This time length is calculated from the formula: **Time_step = 1/(Test Frequency * 5840)**

The "Test Frequency" can be entered from the provided data field on the plotting screen. When testing circuit with very small time constants (RC, RL elements), it is important to use small time steps (or high Test Frequency) otherwise, the circuit response will decay before the next time increment.
Time constant for RC circuits: t = R*C, Time constant for RL circuits: t = L/R.

Fig 11.4 and 11.5 show a couple of simple circuits and their time responses plotted using the FFT method and Nodal Method. The user will notice a good agreement between both methods. Occasionally, the two methods will produce different results, particularly, when the frequency response has sharp, high amplitude peaks. This would require much smaller time steps used by Nodal Method. User editable time steps will be provided in future releases of SoundEasy. The user should be aware, that there is no single best method of analysing circuits in time domain.

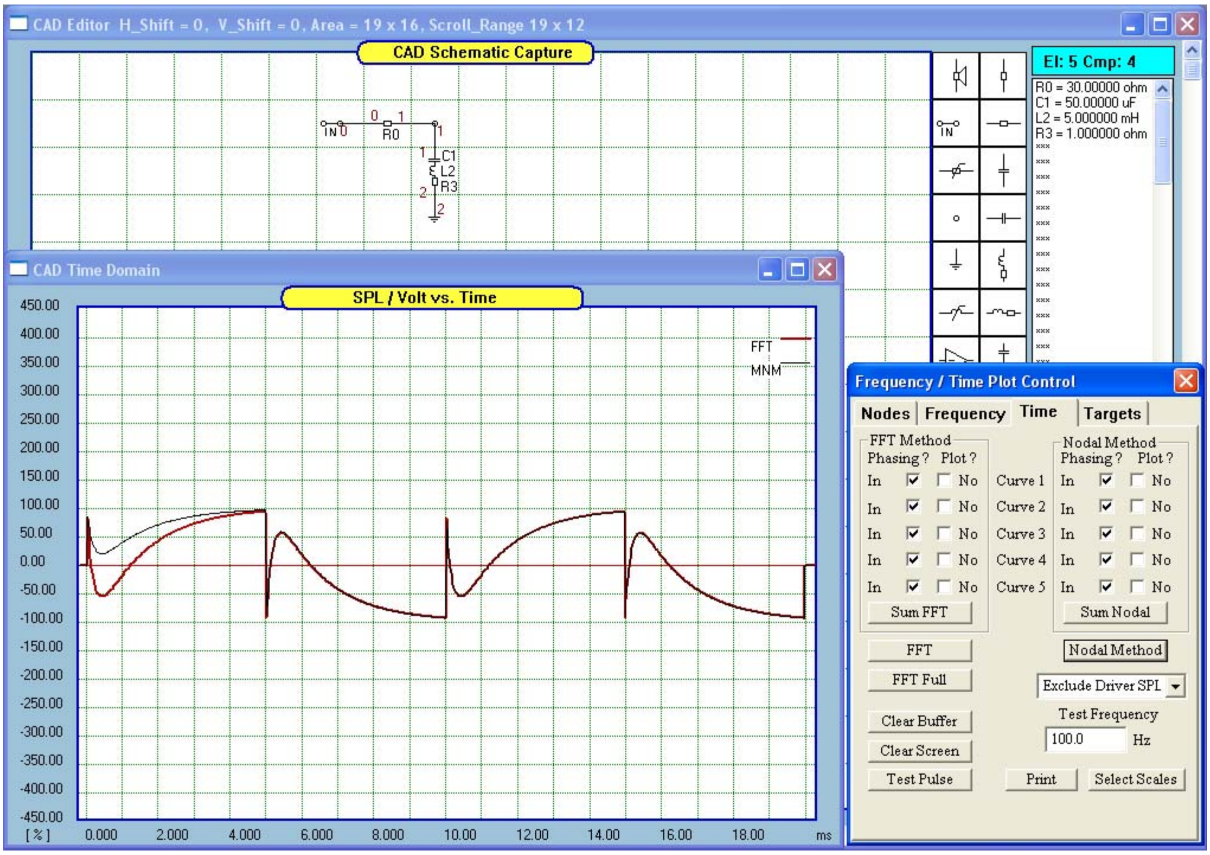

Fig 11.4 Example 1 comparing FFT (brown) and MNM (black).

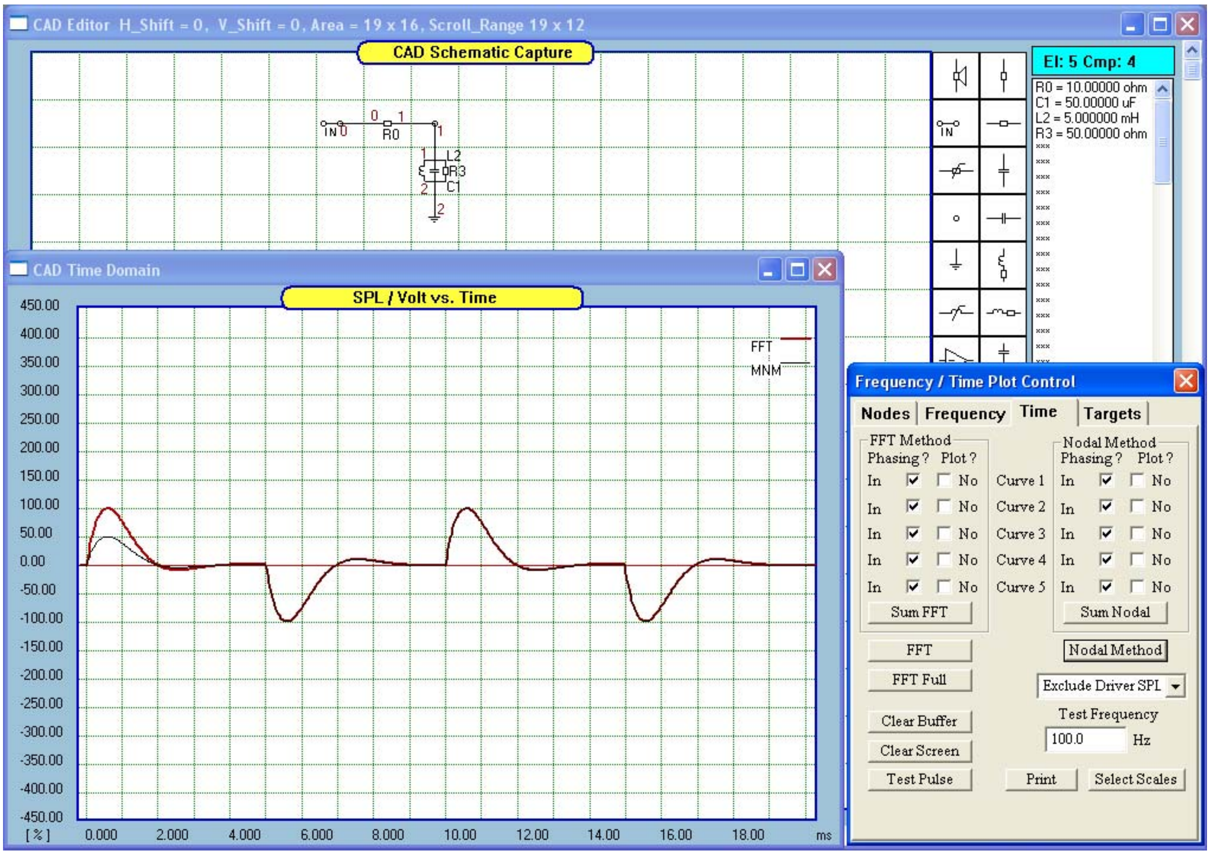

Fig 11.5 Example 2 comparing FFT and MNM

Adding several time responses

The time response function contains a buffer for five time response curves. The user may elect to plot the time response with or without the save option. The saved plots are labelled [SAVED] on the legend. In order to add the curves correctly, all saved plots must have been plotted using the same sampling frequency. Summation process may be performed with the plots being added in phase or out-of-phase. The user will be prompted to select the required configuration from a dialogue box prior the actual summed response being plotted - see Fig 11.1. When the buffer is full, eg: five curves have been saved, it will not accept any more data. To empty (clear) the buffer the user is required to select the "Clear Buffer" option from the floating menu, activated by the "Plot" button.

Concept of "fill-in" driver

Analysis in the time domain usually reveals additional limitations of passive crossovers. In order to overcome these limitations the concept of "filler driver" has been advocated by Bekgaard of Bang & Olufsen.

Fig 11.6 shows frequency responses of o tree-way Butterworth crossover and Fig 11.7 shows time response of the same crossover. It is observable, that the summed time response does not even resemble the expected square wave. This crossover is not a "constant voltage" crossover. The user is encouraged to review several other types of crossovers for the benefit of learning more about their advantages and disadvantages.

One interesting case is depicted on Fig 11.8. The figure shows time responses of a first-order high-pass and low-pass crossovers and their summed response. It is observable, that this crossover is a constant voltage crossover and the resulting summed time response is a perfect square wave. The first order crossover is advocated by many designers as "the best there is" for this reason alone. However, loudspeaker drivers used with the 1-st order crossover must be of highest quality and reliability. They must have high power handling capabilities and be tolerant to out-of-band signals. A selection of drivers meeting these requirements is manufactured by Dynaudio. The "fill-in" driver concept revolves around inserting in an extra driver together with its crossover network - the filler driver. The new combined crossover becomes "constant voltage" crossover.

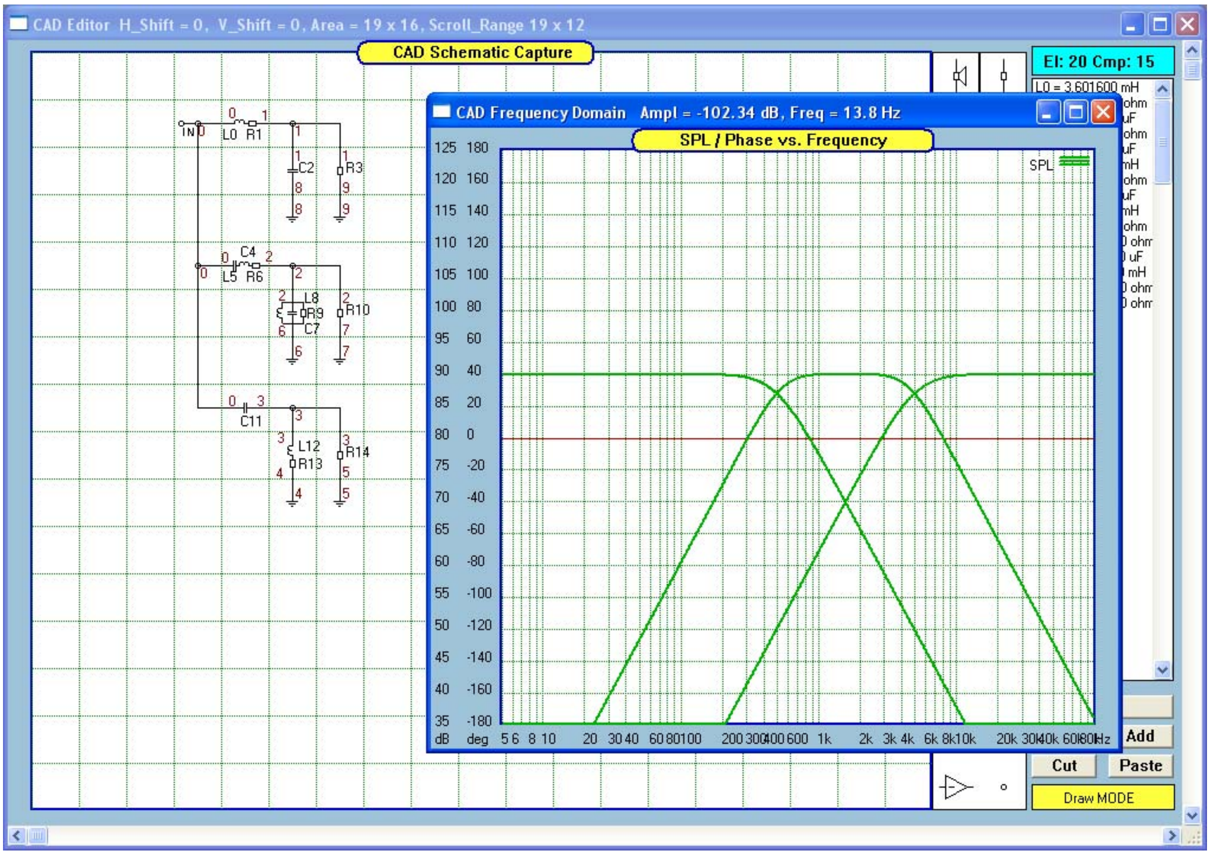

Fig 11.6 Shows frequency responses of o tree-way Butterworth crossover

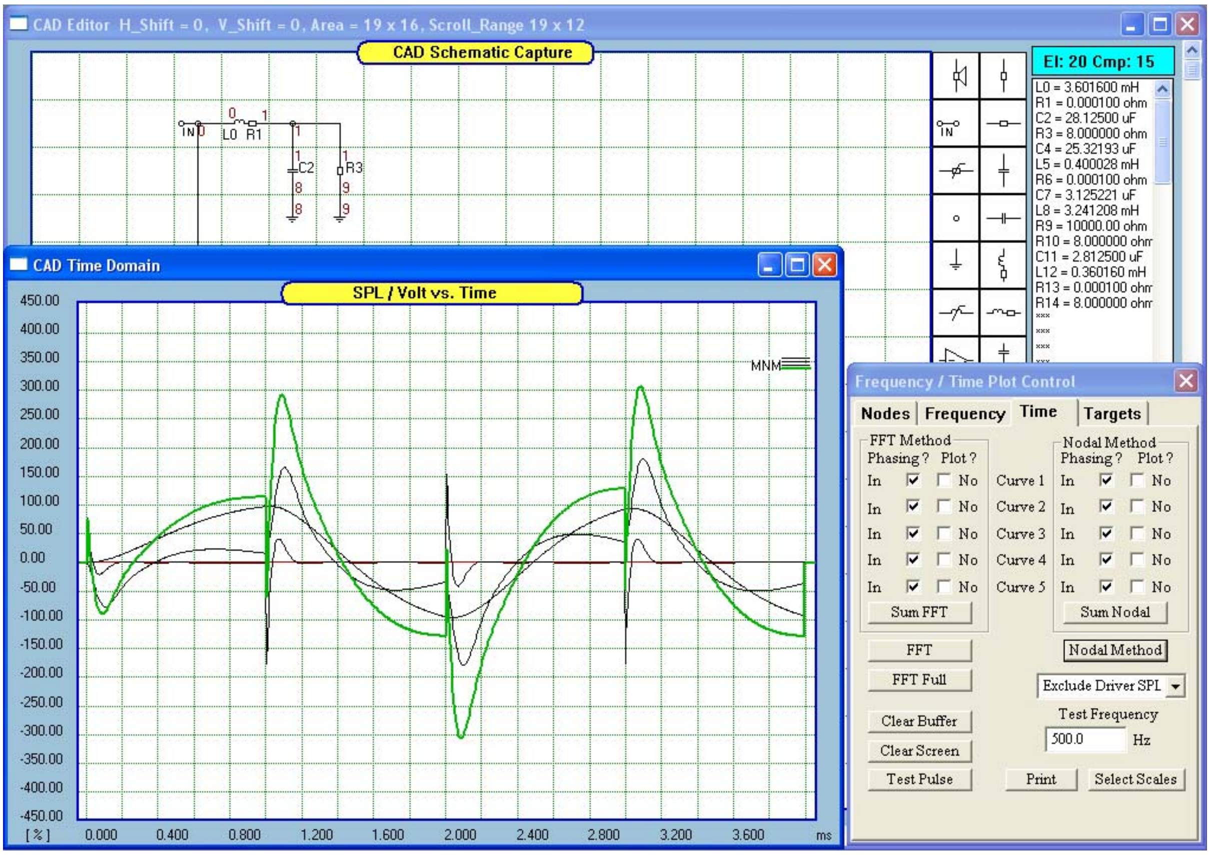

Fig 11.7 Time response of o tree-way Butterworth crossover (Figure 11.6) at 500Hz

Please review the following figures:

1. Fig 11.8
   * Curve 0 - Woofer **second order** low-pass filter frequency response.
   * Curve 1 - Tweeter **second order** high-pass filter frequency response.
   * Curve 2 - Filler driver - **first order** band-pass filter frequency response.

2. Fig 11.9
   * Curve 0 - Woofer time response @ 1000 Hz.
   * Curve 1 - Tweeter time response @ 1000 Hz.
   * Curve 2 - Filler driver time response @ 1000 Hz.
   * Curve 3 - Summed response - a perfect square wave.
   All time plots were added in-phase.

For exact formulas and more technical information about this concept, the user is referred to the original work of Bakegaard (JAS, May 1977, Volume 25, No 5).

You may wish to continue experiments in the following areas:

1. Filler driver connected via +12/-12 dB/oct and higher order band pass filters in 2-way crossover. This research may be beneficial if the filler driver is required to work in higher power systems.

2. Applicability of the filler driver in 3-way and 4-way crossovers of various orders.

3. Time delay filters (Lattice Networks).

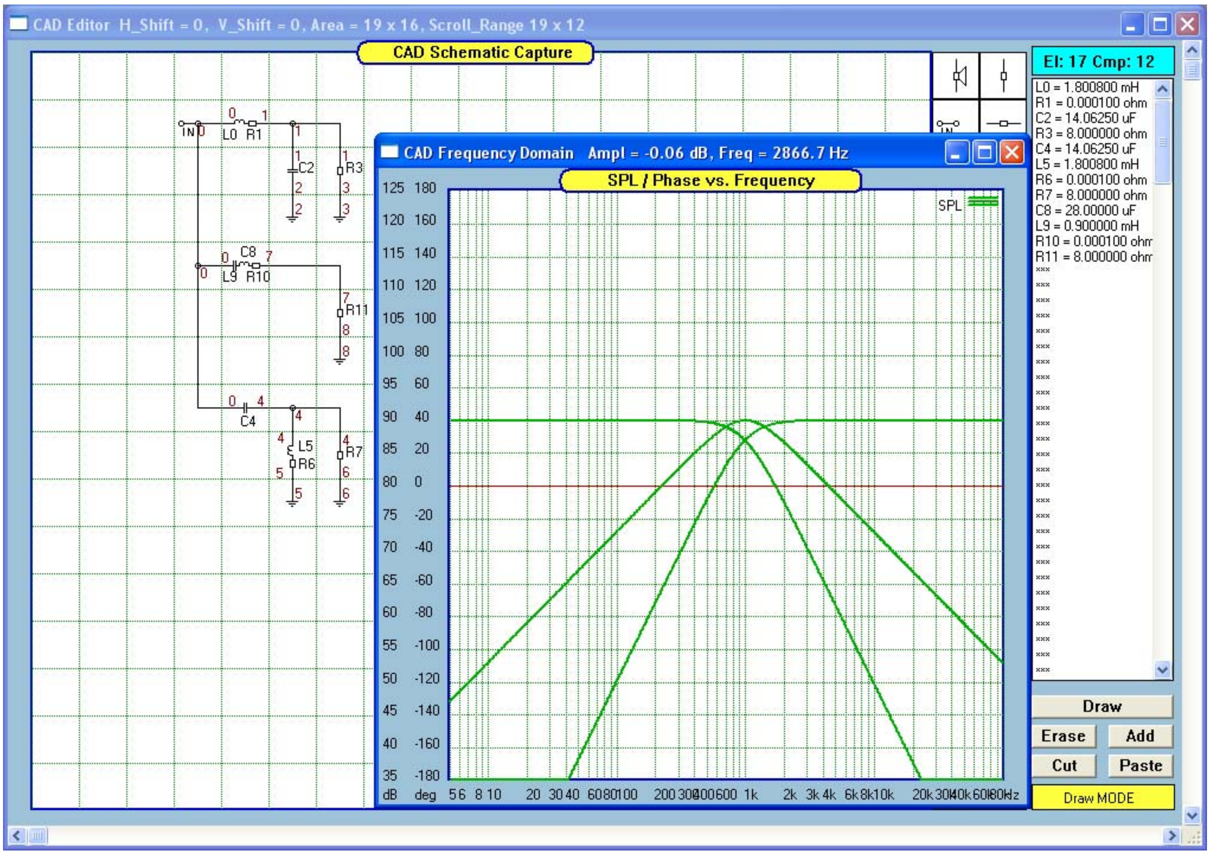

Fig 11.8 Three-way crossover with filler driver

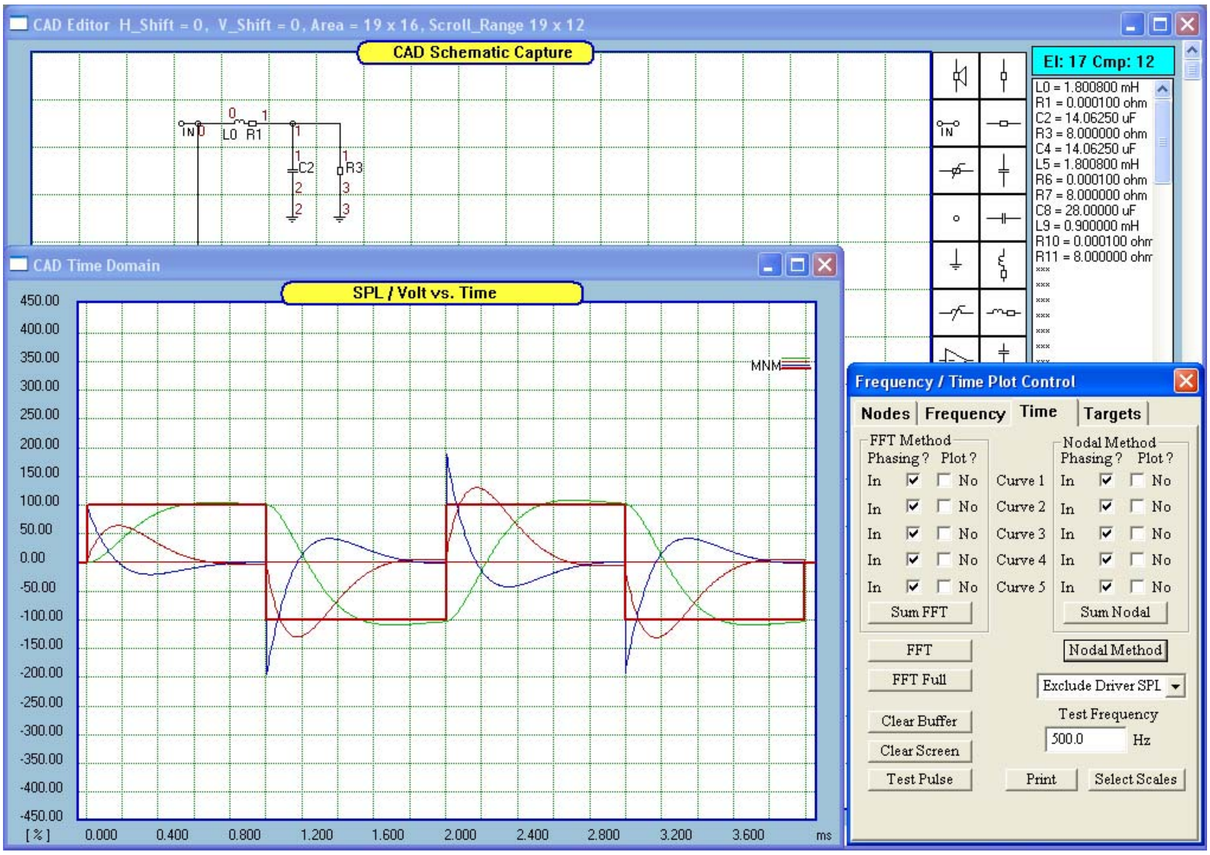

Fig 11.9 Curve 3 - Summed response - a perfect square wave (all drivers in-phase).