Active Crossover Designer Tools for LADSPA
Tutorial and Design Example

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This tutorial illustrates how to set up the loudspeaker model, import data, and then apply various filters to create the crossover for a 2-driver loudspeaker system.

Contents

Initial Setup of the Loudspeaker Model using the ACD-L Tools

The blank workbook ACD-L templates are needed in order to complete these instructions. The loudspeaker model for this tutorial will be constructed using one SYSTEM ON-AXIS RESPONSE workbook, and one DRIVER ON-AXIS RESPONSE workbook per driver in the loudspeaker system. It's a good idea to keep the blank templates in their own directory - you will make a copy of them each time you begin a new project.

Getting the Files Ready in the File System

1. Create a new directory for your project and give it a unique name.

2. Copy both the DRIVER ON-AXIS RESPONSE and SYSTEM ON-AXIS RESPONSE templates and paste the copies into the newly created project directory. The rest of the instructions should be carried out on these copies. If you will be using Open Office Calc, open the template files with Calc, save them as ODF files (the Calc file type extension), and then close the files again – perform the rest of the setup on the ODF files (you may want to save a copy of these files in your template directory for future use).

4. Create copies of the DRIVER ON-AXIS RESPONSE workbooks so that, for each driver in your loudspeaker system, there is a separate file. At this point the files are typically renamed in some logical manner, e.g. for a 3-way system filenames such as "woofer .xls", "midrange.xls", "tweeter.xls", and "system.xls" might be used. You should not rename the files after this point.

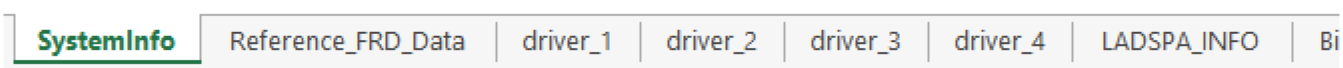
For the purposes of this tutorial, go ahead and rename the files WOOFER, TWEETER, and SYSTEM.

Linking the workbooks together to build the loudspeaker model structure

The frequency grid and sampling rate info

The frequency grid (start and stop frequency of the loudspeaker model) and the sampling rate are controlled from the system workbook. This info is linked into the driver workbooks so that all will be controlled by the values set in the system workbook.

5. Open the WOOFER, TWEETER, and SYSTEM workbooks. Tabs for all the worksheets that are present in each spreadsheet are found at the bottom of the window:



Above, for the system response spreadsheet, and below:

for the driver response spreadsheet.

6. Choose the SystemInfo worksheet in the SYSTEM workbook. Locate, Select and copy cells B9, B10, and B11 (the system response start frequency, stop frequency, and the sampling frequency). Return to the TWEETER workbook and move the cursor to cell B9 (the start frequency). Then perform one of the following:

- For EXCEL use the "Edit > Paste Special > Paste Link" menu item to link the three cells that were copied from the SYSTEM workbook into the current workbook.

- In OPEN OFFICE CALC, use the menu item "Edit > Paste Special" to open the Paste Special dialog box. Check the box under "Options" at the lower left corner next to "Link" and then click the OK button at the top right to create the link.

7. Repeat step 6 for the woofer: copy the cells B9, B10, and B11 from the SYSTEM workbook and perform the same “paste special” operation that was done in step 6 but pasting into the WOOFER workbook.

Linking the driver model data into the system model

The model of the driver response including the effect of the filters used must be communicated from each driver response workbook to the system workbook where they are summed into the model of the output from the loudspeaker system.

9. In the TWEETER workbook, choose the “ComplexResponse” worksheet and select the data in cells A1 through B601 and copy it. In Excel this can quickly be accomplished by starting in the cell A1 and, while continuously holding down the shift key, pressing and releasing first the right arrow key, then the end key, and finally the down arrow key. In Open Office Calc, the data can be quickly selected by starting in cell A1, holding down the control and shift keys, and pressing first the right arrow key and then the down arrow key.

12. Move to the SYSTEM workbook and select the “driver_1” worksheet. You should see the text “DISABLED - INSERT LINK IN COLUMNS A AND B TO ENABLE” in columns A and B. select cell A1 and then use the “paste as link” operation described in step 6 to paste the 601 copied rows of data from the TWEETER workbook into the SYSTEM workbook.

13. Repeat the previous two steps to paste the complex response data from the WOOFER workbook into the driver_2 worksheet in the SYSTEM workbook.

14. The final step is to link the cells that specify the amount of digital delay used for each driver into the LADSPA_INFO sheet of the SYSTEM workbook. Start with the tweeter. Copy cell B32 from the DriverInfo worksheet of the tweeter workbook. Go to the LADSPA_INFO worksheet in the system workbook. As we have done before, use Paste Special > Paste Link to paste the copied value into cell B11 under the heading “Digital Delay” next to the label “Driver 1 NAME”. Now do the same for the woofer. Copy cell B32 from the DriverInfo worksheet of the woofer workbook. Return to the LADSPA_INFO worksheet in the system workbook and use Paste Special > Paste Link to paste the copied value into cell B12 in the “Digital Delay” column next to the label “Driver 2 NAME”. Now whenever digital delay is used as part of the woofer or tweeter crossover filters the value will automatically appear here and the LADSPA text string for the mTAP plugin will automatically be populated in place of the text “no drivers use digital delay” located in cell A16.

15. Set the desired calculation mode. All spreadsheets are supplied (as Excel XLS files) with the “manual” calculation mode selected. When manual recalculation mode is used all formulas in all spreadsheets are NOT recalculated each time you make a change or entry – instead the user must manually force recalculation by pressing the F9 key. This is helpful when multiple edits must be made while updating filter tables, otherwise after each entry you must wait for the automatic recalculation to complete.

   In Excel F9 triggers recalculation of all open spreadsheets. In Calc F9 only triggers recalculation of only the spreadsheet currently in focus – for this reason both manual and automatic mode work well in Excel, while Automatic mode is strongly recommended when using Open Office Calc.

   - For EXCEL: Use the menu item “Tools > Options” to open the options dialog box. In the Calculation tab, choose the desired mode (manual or automatic).
   - For OPEN OFFICE CALC: Use the menu item “Tools > Cell Contents > AutoCalculate” and make sure that the calculation mode is set to automatic. When there is a check mark next to the “AutoCalculate” menu item, the mode is set to automatic. You must still press the F9 key to update the links to the driver response spreadsheets after changes have been made.

16. Save all the open spreadsheets.

Importing FRD Files for the Drivers in the Loudspeaker

1. Locate the driver measurements (FRD files) that accompany this tutorial.
2. Open the WOOFER, TWEETER, and SYSTEM workbooks if they are not already open.
3. In the WOOFER workbook select the Driver_FRD_Data worksheet – it should be empty. Choose one of the following methods to import the FRD data file for the woofer:

FOR OPEN OFFICE CALC OR EXCEL	FOR EXCEL ONLY *
Open the FRD file "blended woofer minphase.frd" accompanying this tutorial in any text editor. Select all the data in the file (omitting the header lines) and then copy the data. Return to the Driver_FRD_Data sheet tab of the woofer DRIVER RESPONSE SPREADSHEET, select cell A1, and then paste the data. In OPEN OFFICE CALC the data import dialog box will be opened and you can choose the file delimiter and other aspects of the import. The data should paste as three columns (A, B, and C). When the data has been imported successfully, proceed to step 5.	Position the cursor in cell A1 of the DRIVER RESPONSE SPREADSHEET for the woofer. For Excel 2003 use the menu command "Data > Import External Data > Import Data…". For Excel 2007 and later, use the "From Text" icon in the Data ribbon. The file to be imported is "blended woofer minphase.frd". Set up the data import – skip the header lines, and select the type of column identifier (fixed column width, tab delimited, space delimited, etc.) so that the FRD file is imported as three columns (frequency, SPL, phase) into columns A,B, and C of the worksheet. When the data has been imported successfully, proceed to step 5.

* Also, for EXCEL ONLY, an ACD extension called the "FRD File Import-Export" extension, that streamlines and simplifies ACD file importing and exporting tasks. The extension is an Excel spreadsheet and works on all spreadsheets that are open in the same instance of Excel on your computer. See the ACD web page for more information and to download the extension.

4. Import the FRD data file "blended tweeter minphase.frd" into the TWEETER workbook using the same procedure as in step 4.
5. At this point, let's check to make sure that the imports were successful: select the SystemInfo worksheet in the SYSTEM workbook, scroll down to bring the System Magnitude plot into view, and recalculate (press F9). Because this may require a complete recalculation of every cell in all open worksheets, this recalculation may take a bit longer to complete than usual. Once the recalculation is complete, you should see a plot similar to the one shown below in Figure 1. If problems are encountered, please read the technical manual section "troubleshooting problems" for some hints, or request help at ACD@claub.net (make sure to be specific in your EMail about the nature of the problem).

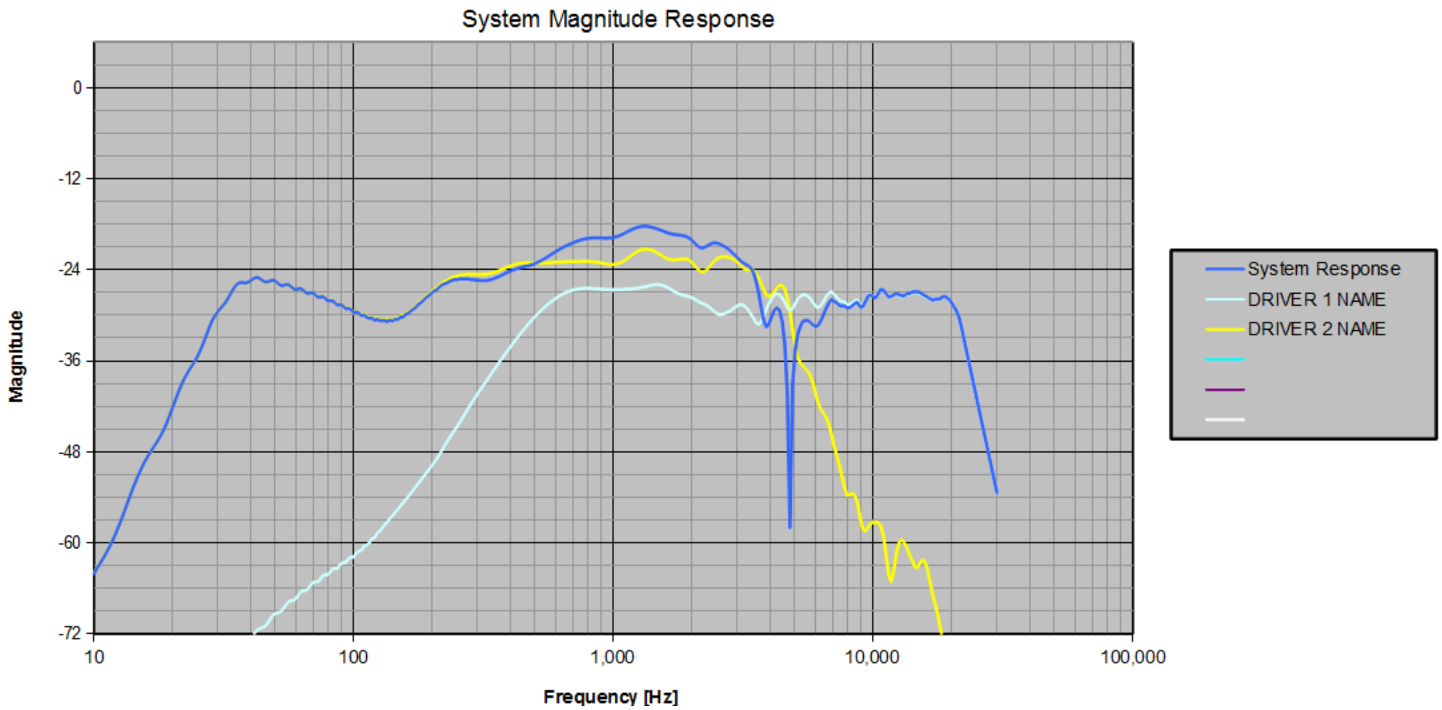


Figure 1: Plot of the System Magnitude Response with woofer and tweeter data successfully entered in to their respective spreadsheets, and those spreadsheets correctly linked in to the system response spreadsheet.

6. Next we will import the FRD data file "woofer and tweeter no filters.frd" into the ReferenceResponse worksheet of the SYSTEM workbook in a similar fashion to the FRD data imports for the woofer and tweeter. You can use either the method outlined in step 4 to perform the import. The imported FRD data should start in cell A1 as before.

7. Let's also update the labels for each driver in the plot legend. In the SYSTEM workbook, select the driver_1 worksheet and find cell F1 containing the blue text "DRIVER 1 NAME". This cell is used in the plot legend, and we should change it to something more descriptive. Enter the text "Dayton RS28F". Next, select the driver_2 worksheet, position the cursor in cell F1 and enter "Peerless 850137". Returning to the SystemInfo worksheet, you should find that the plot legend has updated and looks like the plot shown in Figure 2, below, including the Reference Response (white) line.

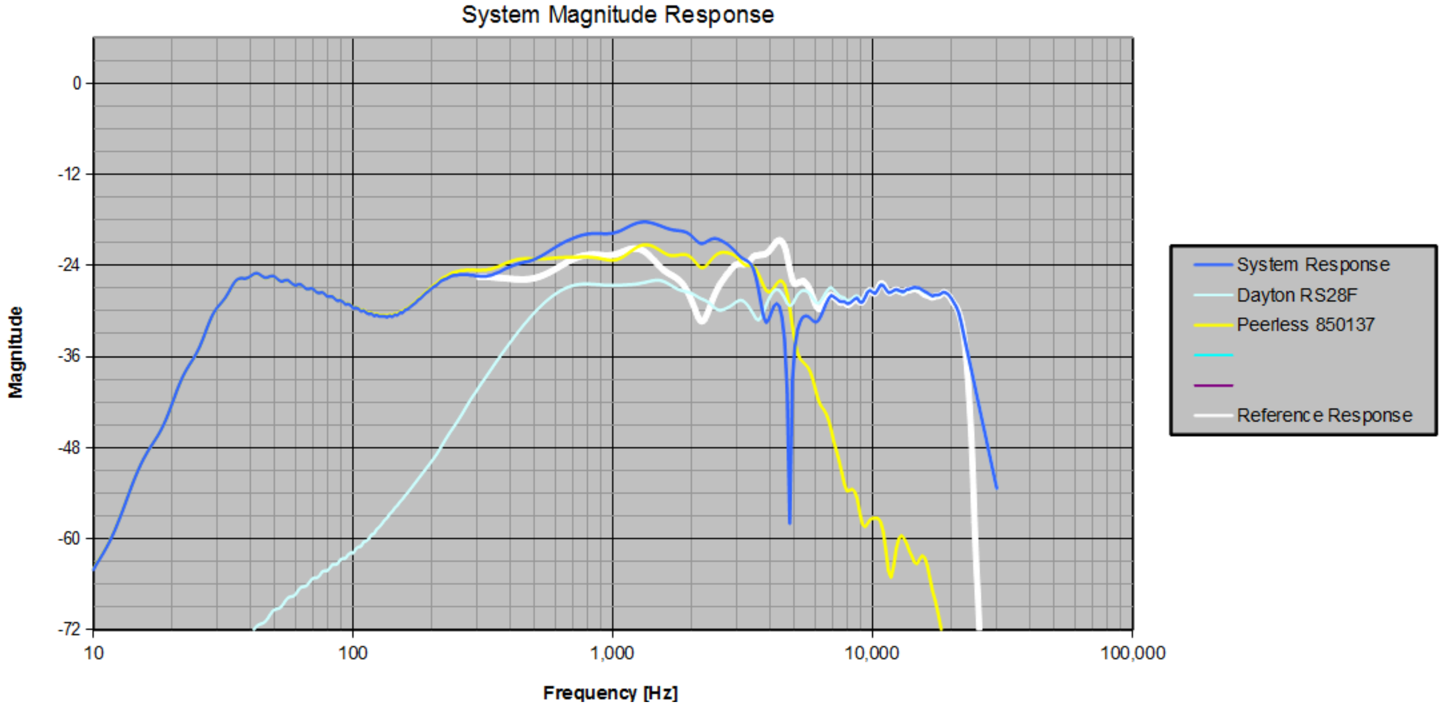


Figure 2: Plot of the System Magnitude Response with all data from this tutorial successfully entered.

Determining the Acoustic Delay and Polarity for each Driver

The next step is to determine the acoustic delay for the woofer. The goal is to get the blue "system response" line to overlay the white "reference response" line. The reference response contains the data obtained when a measurement was taken with both the tweeter and woofer reproducing the same signal. The ACD tools combine the woofer and tweeter responses into the "system response" including the acoustic delay specified for each driver. When supplied with an accurate set of measurements, the system and references responses will only overlap when the acoustic delay and driver polarities in ACD correspond to the system that was measured.

Manual Method

8. Return to the DRIVER RESPONSE SPREADSHEET for the woofer, and find the Driver Characteristics input area in the DriverInfo worksheet, as shown below.

DRIVER CHARACTERISTICS	
ACOUSTIC DELAY WITH RESPECT TO REFERENCE PLANE:	
0.123	driver acoustic delay in milliseconds
344	speed of sound in meters per second
4.23	equivalent driver physical offset in centimeters
1.67	equivalent driver physical offset in inches
POLARITY OF DRIVER VOICE COIL WIRING:	
1	**1** = normal polarity, **–1** = reversed polarity

Enter different values for the acoustic delay (cell G7), for example 0.05, 0.10, 0.15, and 0.20, and change the voice coil polarity (cell G12) of the woofer or the tweeter to see the influence of these parameters. Each time you enter a new value, return to the System Magnitude Response plot in the SYSTEM RESPONSE SPREADSHEET and press F9 to recalculate. The system magnitude (blue line) shows the ACD model of the summed woofer and tweeter responses for the value of the acoustic delay and driver polarity that you have entered. The Reference Response (white line) is what was measured in the real world. The goal is to find the value for which the blue and white lines overlap everywhere.

You will find that an acoustic delay of about 0.14 milliseconds, with the polarity of both the woofer and tweeter set to "normal" results in the best overlap between the measurement (white reference response line) and the simulation of the loudspeaker output (blue line).

Once the acoustic offset has been identified, do not make any further changes to the values in the Driver Characteristics area for either driver. These are characteristics of the relative arrangement of the drivers in space due to their mounting in a baffle and the placement of the microphone that recorded the measurements. Because the influence of distance has been captured in the measurements, there is no need to enter the actual distance to the drivers or their coordinates in space and only the acoustic delay and voice coil phase polarity is needed to accurately relate the measurements to the physical loudspeaker system.

The System Magnitude Response plot should now look like Figure 3, with the blue and white lines overlapping.

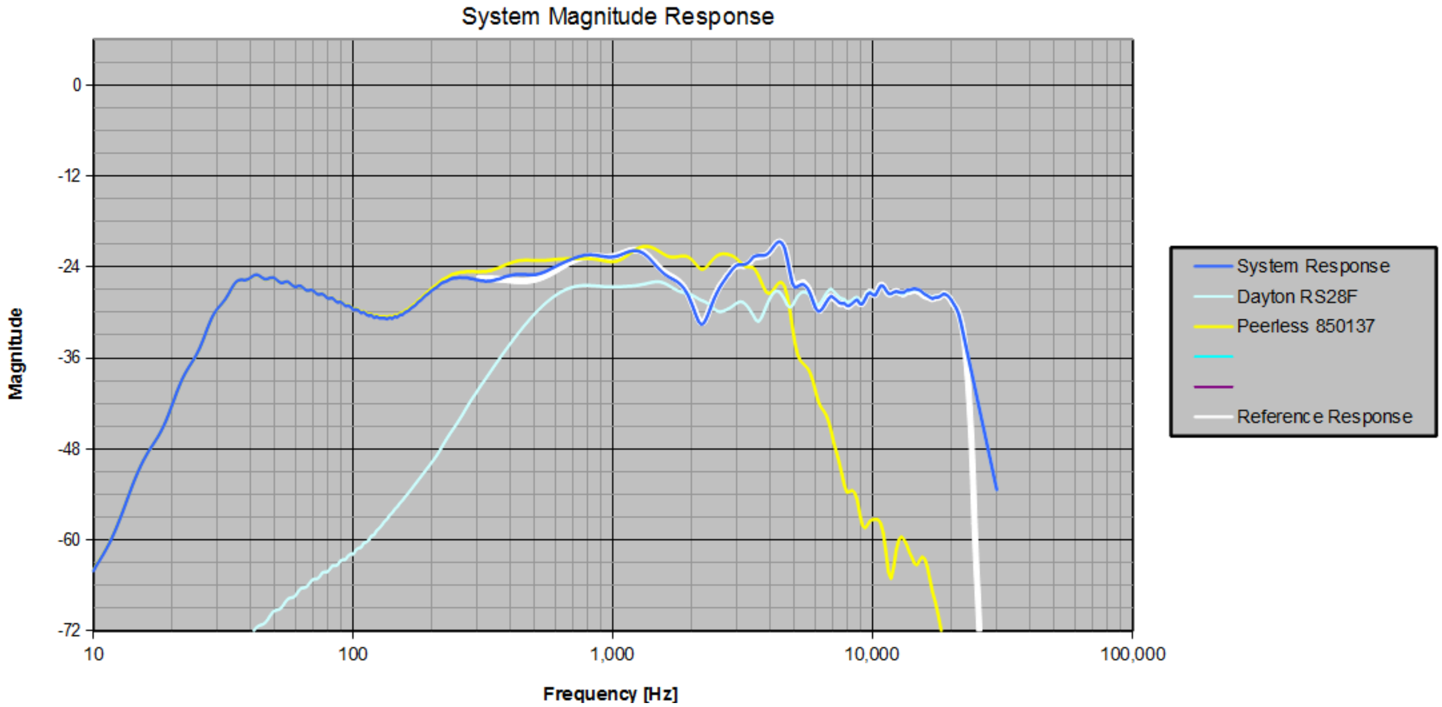


Figure 3: System Magnitude Response plot showing good agreement between the measured (white) and calculated (blue) responses for the woofer and tweeter when the woofer acoustic delay is 0.14 milliseconds.

9. At this point, we no longer need to see the reference response data on the system magnitude response plot in the SystemInfo worksheet, so let's remove it. In the ReferenceReponse worksheet of the SYSTEM RESPONSE SPREADSHEET, select columns A, B and C and then press delete to remove the data. The reference response data will be cleared from the System Magnitude Response plot the next time that you press F9.

Automatic Method

For Excel users that have the SOLVER add-in installed and enabled, ACD-L can automatically determine the polarity and acoustic offset. This can be done using measurements taken on pairs of drivers (formerly the only way) or for measurements taken on all drivers in the system (now possible in ACD-L).

In the System Response workbook, find the sheet named "DP_Finder". You will see at the top a table, and below two plots. There is also a button labeled "RUN SOLVER". This is the interface that you will use to automatically determine the offsets and phase for the drivers in your loudspeaker.

The first step is to link the cells of the table in the DP_Finder sheet to the corresponding cells in the Driver_Info sheet of each Driver Response workbook. Let's start with the tweeter. Copy cell D12 from DP_Finder. The contents of cell D12 can be left blank at this time. Switch to the workbook for the tweeter and find cell G13. Select cell G13 and right click or use the menus to Paste Special > Paste Link. This will update the Tweeter's polarity with the value in the table in the DP_Finder sheet each time it is changed. Next, we link the delay. Find Cell D13 in the DP_Finder sheet and copy it. Return to the Driver_Info sheet of the tweeter's Driver Response workbook and find cell G8. Select the cell and the right click or use the menus to Paste Special > Paste Link. This links the cell from the DP_Finder sheet to the Driver Response sheet. Repeat the above linking steps for the other drivers in the loudspeaker, copying the (blank) cell from DP_Finder and pasting as a link into the driver's Driver_Info worksheet.

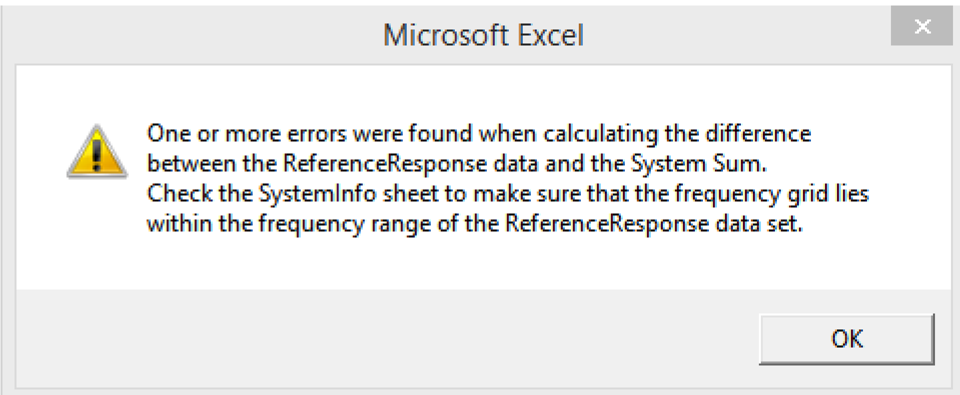
Now we need fill in two initial value in the table in the DP_Finder sheet to establish the references for the loudspeaker model in terms of delay and phase. In this example, let's choose the tweeter for both references. Because they are references and the values used here are relative, we enter a 0 (zero) for delay and 1 (one) for the polarity, meaning that the tweeter acoustic center is located on the zero delay reference plane, and its polarity (whatever that may be) with respect to the electrical input is the reference for “normal” phase polarity.

It’s important to keep in mind that after this process has been completed the leads connecting the amplifiers and drivers should not be reversed, since this would reverse the phase. Also, for some amplifiers the polarity of their output (speaker connections) is reversed compared to the polarity at the input. If you change amplifiers or use multiple amplifiers, this can be something to check.

We are now ready to determine the other values. The table should look like this:

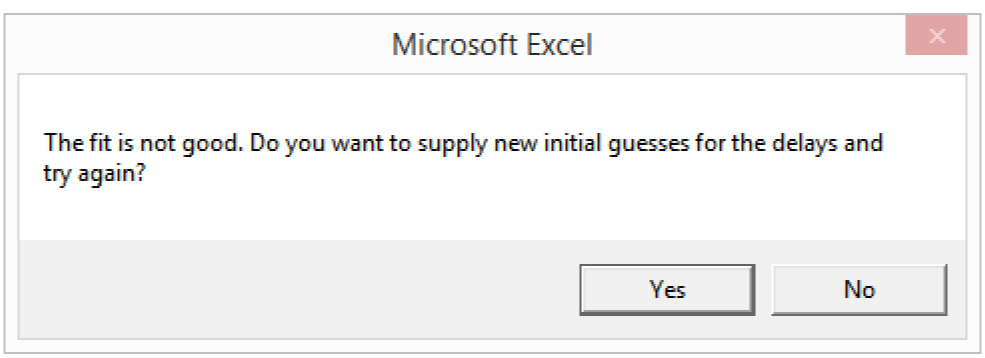
	driver_1	driver_2	driver_3	driver_4
POLARITY:	1			
DELAY:	0			

Click on the “RUN SOLVER” button. The following message may appear.

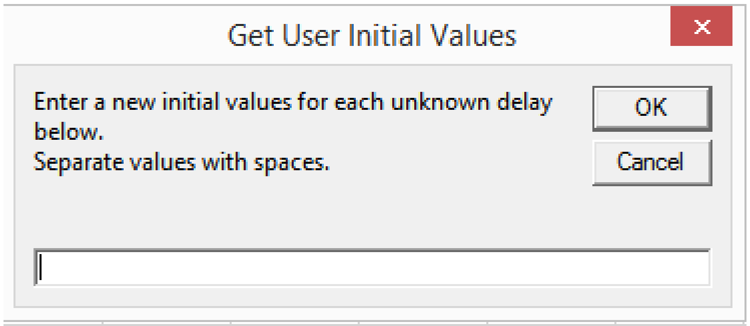


This message is generated when errors are encountered in the worksheet calculation of the difference between the reference response data and the system sum. In this case, the ReferenceResponse data set that we are using begins at 299Hz, however, the frequency grid that we currently are using is 20Hz to 20kHz. Because part of the system frequency grid lies outside the range of the reference response data, it can’t be interpolated onto the frequency grid and the formula returns an error. To solve this, we make sure that the frequency grid that is set up in the System workbook on the SystemInfo sheet lies within the frequency range of the ReferenceResponse data set. If you encounter this error message, return to the SystemInfo sheet and change the start frequency of the frequency grid, in this case to 300Hz. Leave the end frequency at 20,000 Hz. Press F9 to recalculate the worksheets. The original frequency grid can be restored when you are ready to develop the crossover.

Return to the DP_Finder sheet and click on the “RUN SOLVER” button again. This time the code should run. If the error value is not sufficiently low, you will be propted to try again using different guesses at the delay values. If that is the case, you will see the following message:



Answering yes will bring up another dialog box where you can enter new guesses for the delays:

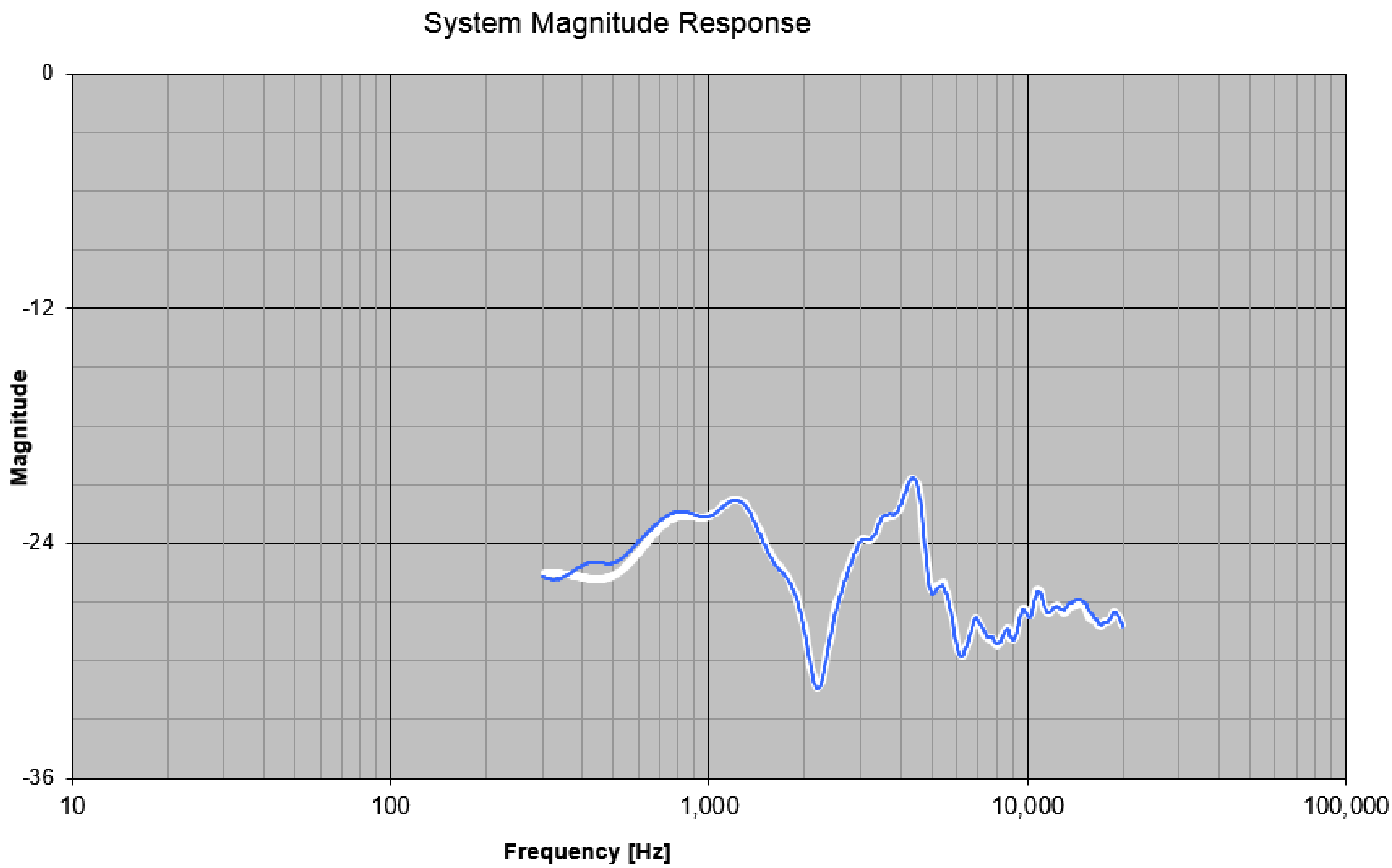


Enter only the “unknown” delays, separated by a space. In this case there is only one unknown (the woofer delay since the tweeter is the reference plane for all other delays) and you would enter one value. For a multiway system you could enter up to 3 values, since 1 driver is always used as a reference. Clicking OK in this dialog box will restart the optimzation routine. Some difficult fitting problems may require accurate guesses at the delay values but many should be able to be fit in one pass using the default initial values. To get an estimate of the delay you can start over with using the manual method and return when you have established ballpark values. The fitting routine will then finish off the process for you, with high precision.

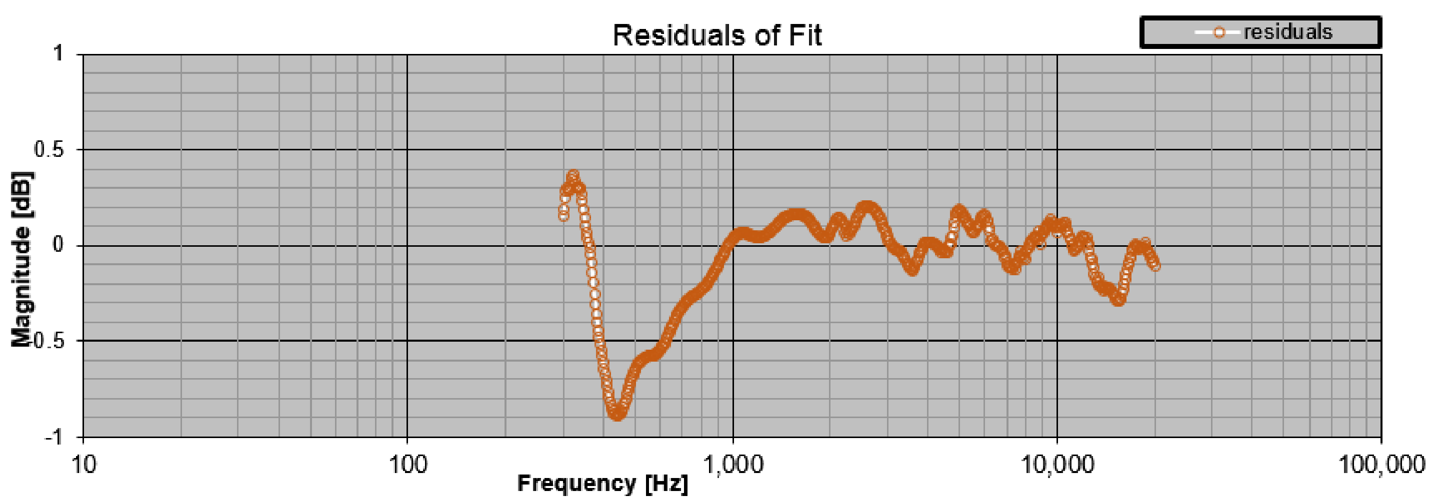
At this point you should have been able to get the solver to optimize the delay value and find the correct polarity. From the manual method, we know that the polarity is the same as the tweeter (normal polarity) and the delay is approximately 0.14 milliseconds. If you optimized the delay in the interval between 300Hz and 20kHz, you should see the table look like this:

	driver_1	driver_2	driver_3	driver_4
POLARITY:	1	1		
DELAY:	0	0.135772		

The delay has been optimized to 0.1358 milliseconds. Below are two plots. The first shows the fit:



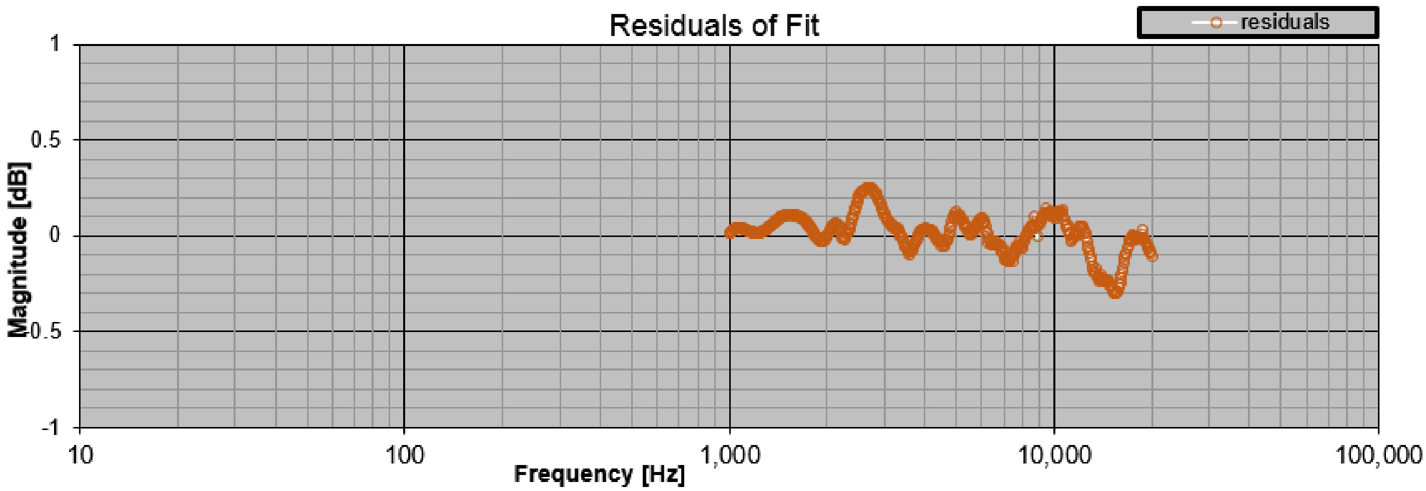
The second plot shows the residuals of the fit:



You can see by the residual plot that above about 1kHz the residuals are clustered around 0 with a very slight downward trend. In constrast, below 1kHz there is a large deviation. This indicates that the fit is somewhat poor below 1kHz and above on the fit plot you can see that this is the case. The reason for this is that the tweeter and woofer data used for this fit have been processed and corrected for low frequency errors, while the woofer+tweeter data set used for the reference response has not been corrected in this way and is the “as collected” data which has inherent low frequency errors due to the limitations of making an indoor frequency response measurement. This is the source of the fit deviation we are experienceing.

Because the woofer’s response extends well into the tweeters’ range, we can eliminate the data below 1kHz and still get a good fit. To do this, return to the SystemInfo tab and set the start of the frequency grid to 1kHz.

Recalculate the worksheet by pressing F9. Return to the DP_Finder sheet and clear the cells containing the polarity and delay for the woofer. Finally repeat the automatic process to determine polarity and delay for the woofer. The result should be a delay of 0.1350, slightly different than the previous value. The difference is only in the fourth significant figure of the woofer delay, which would not have an impact on the loudspeaker model. The residuals of the fit have been improved slightly as well:



In this case the exclusion of the low frequency part of the data sets has not had a major impact. If your fit is very poor at low frequencies, this is one way to improve it. This is only something that you need to if you have to. Most of the time the data will be fit very well using the automated method, and it is especially helpful to fine tune the delay value, or when there are multiple drivers being fit at the same time. In that case the manual method can be quite tedious.

Now that we are done with the automatic process, you can reset the start frequency of the frequency grid to 20Hz in the SystemInfo sheet and delete the ReferenceResponse data. Do that now before moving on to the next section.

Developing a Crossover

Now that the acoustic delay has been determined, we are free to develop a crossover. This system is a 2-way using an 8" woofer and a 1" dome tweeter and the crossover point should be somewhere between 1.5k Hz and 2.5k Hz. You will need to enter one or more low-pass filters for the woofer, one or more high-pass filters for the tweeter, and possibly one or more delay stages for the tweeter. Also, some adjustment of the relative levels of the drivers is likely needed. The following steps provide an overview on how to build a crossover by entering filters in the woofer, tweeter, and system Filter Tables.

Getting Started

10. Let's try a 4th order Linkwitz-Riley crossover at 2k Hz. To find out what filters are used in an LR4, consult the section of the manual **Using Filters to Construct Crossovers > Loudspeaker Crossovers using Butterworth or Linkwitz-Riley Filters**. You will see the following table:

	1st order stage	second order stage #1 Q	second order stage #2 Q	second order stage #3 Q	second order stage #4 Q
LR2		0.5			
BUT2		0.707			
BUT3	✓	1			
LR4		0.707	0.707		
BUT4		0.54	1.31		
BUT5	✓	0.62	1.62		
LR6		0.50	1.00	1.00	
BUT6		0.52	0.707	1.93	
BUT7	✓	0.55	0.8	2.24	
LR8		0.54	0.54	1.31	1.31
BUT8		0.51	0.60	0.90	2.56

Table 1: some loudspeaker crossovers and the filters needed to implement them in ACD

Reading across the table, you can see that an LR4 crossover requires two second order filters, each with a Q=0.707. The filter corner frequency is equal to the crossover point for LR type crossovers. A textbook LR4 crossover consists of a pair of high-pass filters (filter type 22) for the tweeter, and a pair of low-pass filters (filter type 21) for the woofer. We enter this information in the filter tables for the woofer and the tweeter to construct the LR4 crossover.

First go to the Filter Table for the tweeter, in the DriverInfo worksheet of the TWEETER workbook. Enter the values into Filter 1 and Filter 2 as shown below:

	Filter 1	Filter 2	Filter 3	Filter 4	Filter 5	Filter 6	Filter 7	Filter 8
type:	22	22	0	0	0	0	0	0
gain [dB]:	0	0	0	0	0	0	0	0
polarity*:	1	1	1	1	1	1	1	1
Fop:	2000	2000	1	1	1	1	1	1
Qp:	0.707	0.707	1	1	1	1	1	1
Foz:	1	1	1	1	1	1	1	1
Qz:	1	1	1	1	1	1	1	1

* NOTE: for polarity enter 1 for normal polarity and -1 (or anything except 1) for reversed polarity

Above: the tweeter Filter Table containing parameters for a 4th order Linkwitz-Riley high-pass filter.

We now need to enter the corresponding LP filters for the woofer. Go to the Filter Table in the DriverInfo worksheet of the WOOFER workbook. Enter the values into Filter 1 and Filter 2 as shown below:

	Filter 1	Filter 2	Filter 3	Filter 4	Filter 5	Filter 6	Filter 7	Filter 8
type:	21	21	0	0	0	0	0	0
gain [dB]:	0	0	0	0	0	0	0	0
polarity*:	1	1	1	1	1	1	1	1
Fop:	2000	2000	1	1	1	1	1	1
Qp:	0.707	0.707	1	1	1	1	1	1
Foz:	1	1	1	1	1	1	1	1
Qz:	1	1	1	1	1	1	1	1
* NOTE: for polarity enter 1 for normal polarity and -1 (or anything except 1) for reversed polarity								

Above: the woofer Filter Table containing parameters for a 4th order Linkwitz-Riley low-pass filter.

We have now entered the filters for an LR4 type crossover at 2k Hz. Let's see what kind of system response we get from this. Return to the SystemInfo worksheet in the SYSTEM workbook and press F9. The plot should be similar to Figure 4.

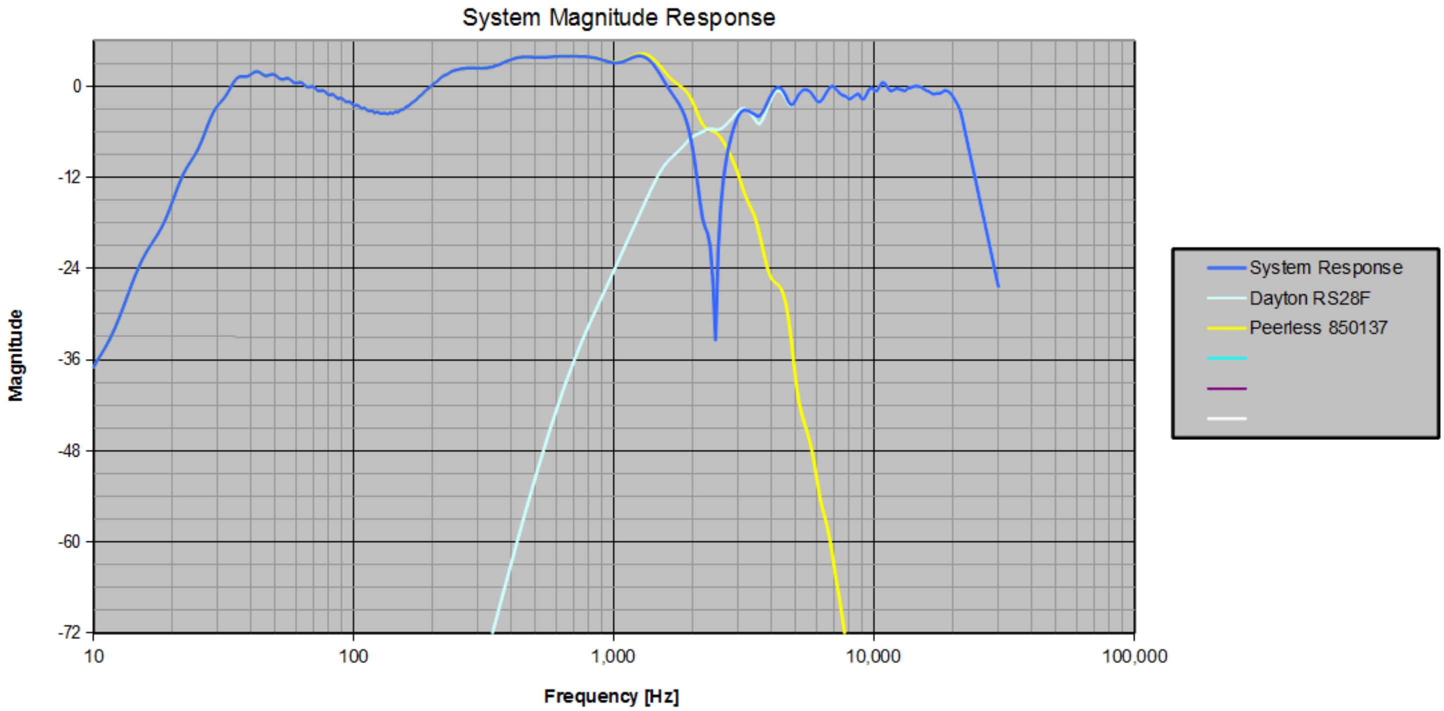


Figure 4: System response using a 4th order Linkwitz-Riley crossover at 2k Hz.

This doesn't look great, but it's not as bad as it might first seem. The frequency response actually looks like what you get with a reverse polarity connection, with a deep null around the crossover point. Also, we still need to address the difference in level between the woofer and tweeter in the vicinity of the crossover point. So, let's try to reverse the polarity of the tweeter, and reduce the gain of the woofer by around 3-4 dB.

To reverse the tweeter polarity we will change the polarity of one of the filter stages. In the DriverInfo worksheet of the TWEETER workbook, find the Filter table and enter -1 (negative one) for the polarity of one of the filters to reverse the polarity of the tweeter. When the polarity is reversed, the message below the Filter and EQ tables changes to:

THE ACOUSTIC POLARITY IS REVERSED WITH RESPECT TO THE INPUT SIGNAL POLARITY

Return to the Filter Table in the WOOFER workbook. In the column for Filter 3, enter "-4" in the row corresponding to "gain [dB]".

Let's also bring the response levels shown in the magnitude response plot in the SYSTEM RESPONSE SPREADSHEET up to around 0 dB to make it easier to examine the variations in SPL level. Return to the SystemInfo worksheet of the SYSTEM workbook. Find cell B34 in the section titled **SYSTEM RESPONSE MAGNITUDE SCALING FACTORS**. Enter 27 to increase all driver responses and the system response by 27 dB. Now press F9 to see the effect of these changes. The plot should now look like Figure 5.

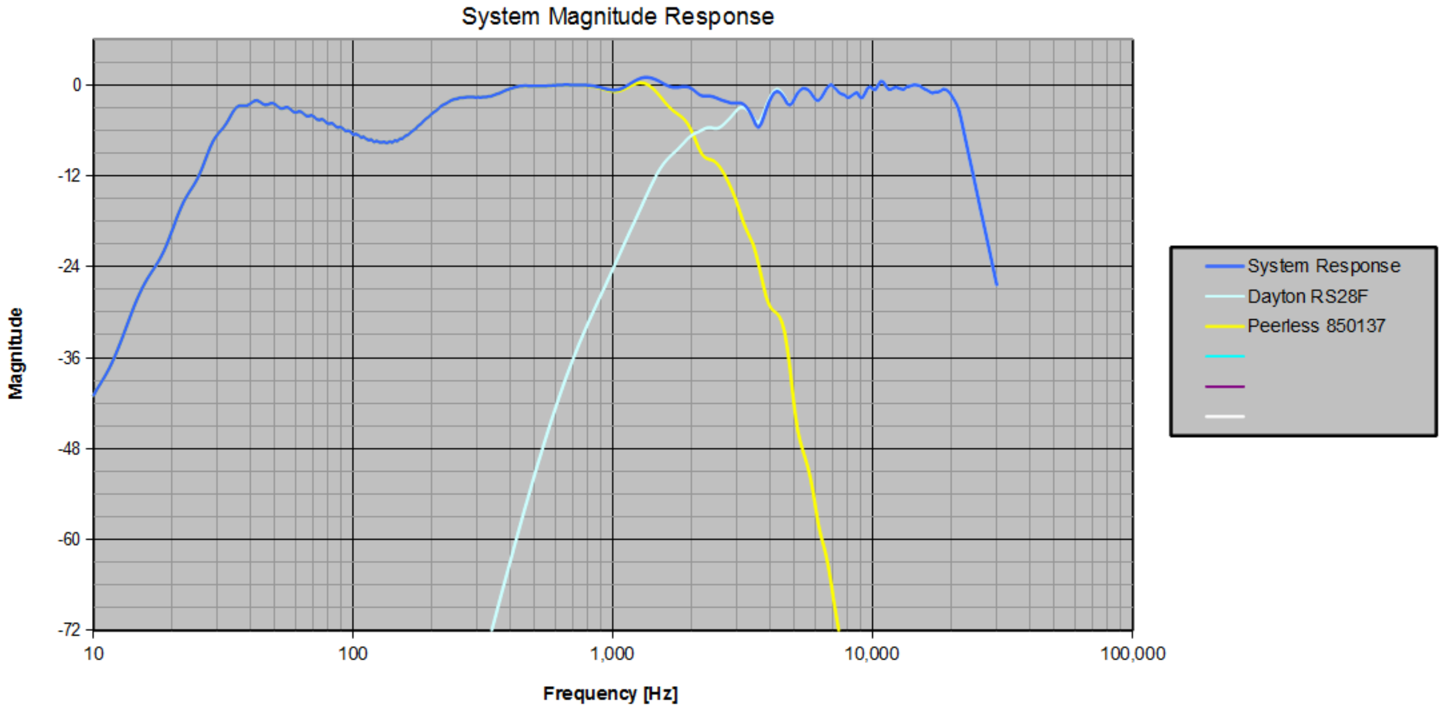


Figure 5: Frequency Response of loudspeaker with LR4@2k Hz crossover, reversed tweeter polarity and woofer gain reduced by 4 dB.

Improving the Frequency Response near the Crossover Point

We are getting closer to a flat frequency response. The drivers are in phase at the crossover point (sum is +6dB at 2000 Hz), however, there are some problems that need to be addressed. The tweeter response is drooping between 2000 and 3500 Hz and needs some boost. An easy way to do this is to increase the Q of the high-pass filters. Return to the Filter table for the tweeter and change the Q from 0.707 to 1.0 for both Filter 1 and Filter 2. Return to the SystemInfo worksheet of the SYSTEM workbook and press F9 to see the changes in the response, as shown below in Figure 6:

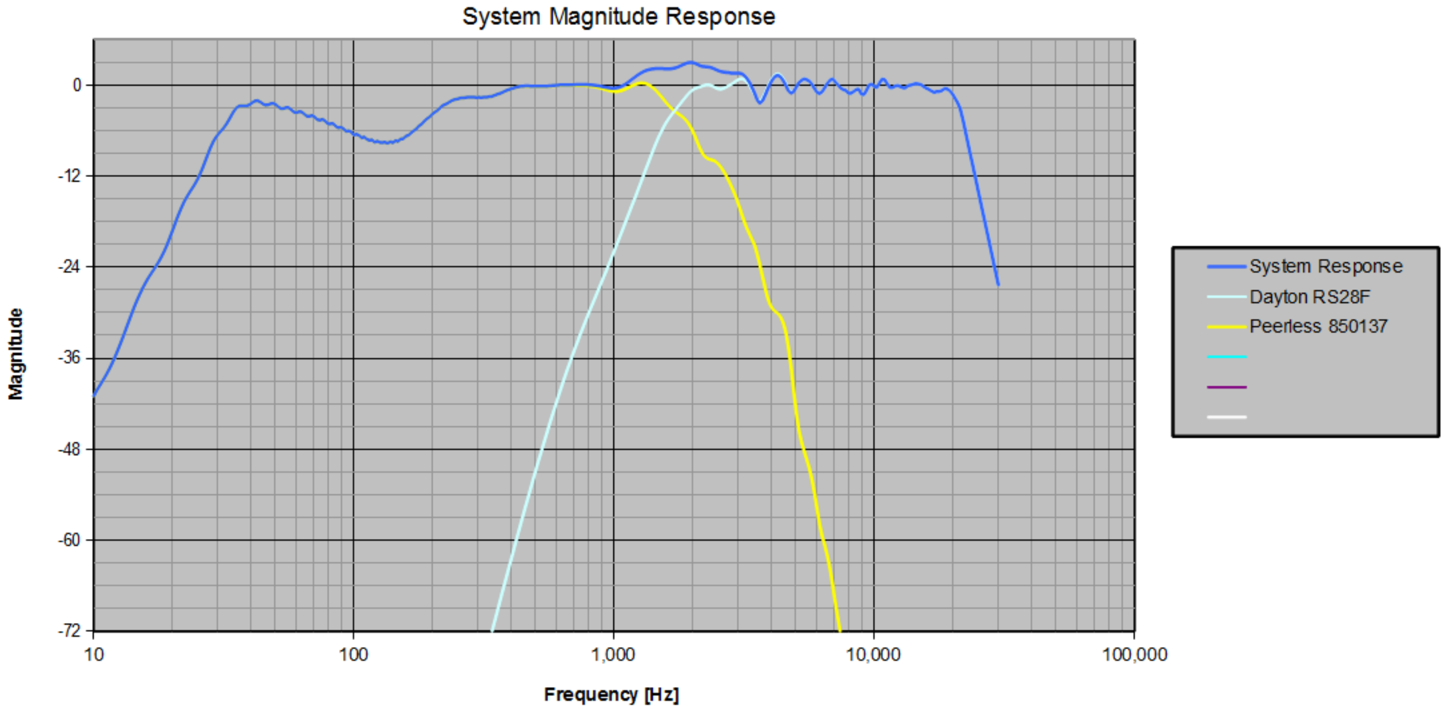


Figure 6: Frequency Response of loudspeaker with modified tweeter filters, reversed tweeter polarity and woofer gain reduced by 4 dB.

The tweeter response is looking better, but now we have created a hump in the frequency response. Let's try to get rid of the hump by moving the filter corner frequencies for the woofer down a bit, and increasing the Q at the same time, which results in a steeper cutoff. Return to the Filter table for the woofer and change the Q from 0.707 to 1.0 and the corner frequency (Fop) to 1250 Hz for both Filter 1 and Filter 2. Return to the SystemInfo worksheet of the SYSTEM workbook and press F9 to see the changes, as shown in Figure 7.

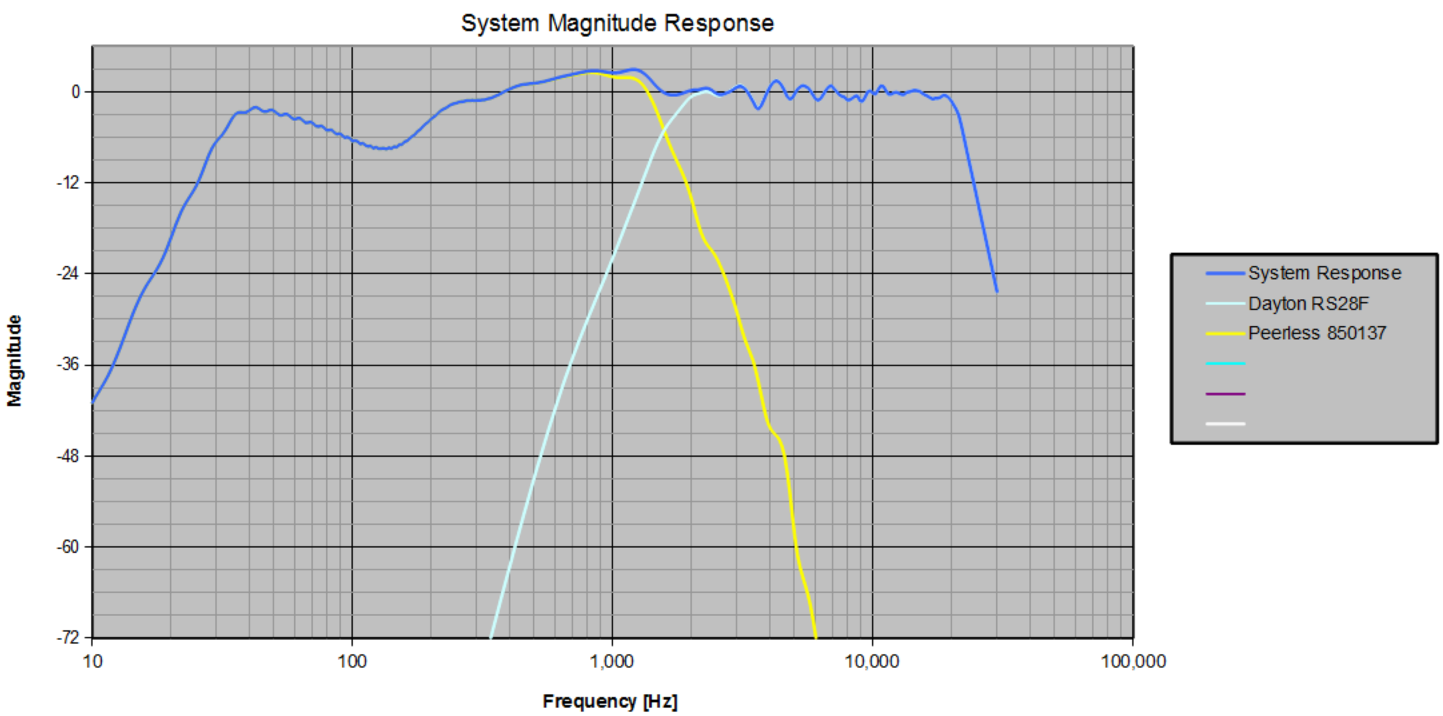


Figure 7: Frequency Response of loudspeaker with modified tweeter filters, modified woofer filters, reversed tweeter polarity and woofer gain reduced by 4 dB.

It might appear that this has only created a different shaped hump, but it's is really a result of the mismatch in the woofer and tweeter levels at the crossover point (which has now dropped to about 1600 Hz). We can improve the crossover region level matching between the tweeter and woofer by reducing the woofer level by another 3dB. Return to the Filter table for the woofer. In the column for Filter 3, change the value to -7 in the row corresponding to "gain [dB]". Return to the SystemInfo worksheet of the SYSTEM workbook and press F9 to see the changes, shown below in Figure 8.

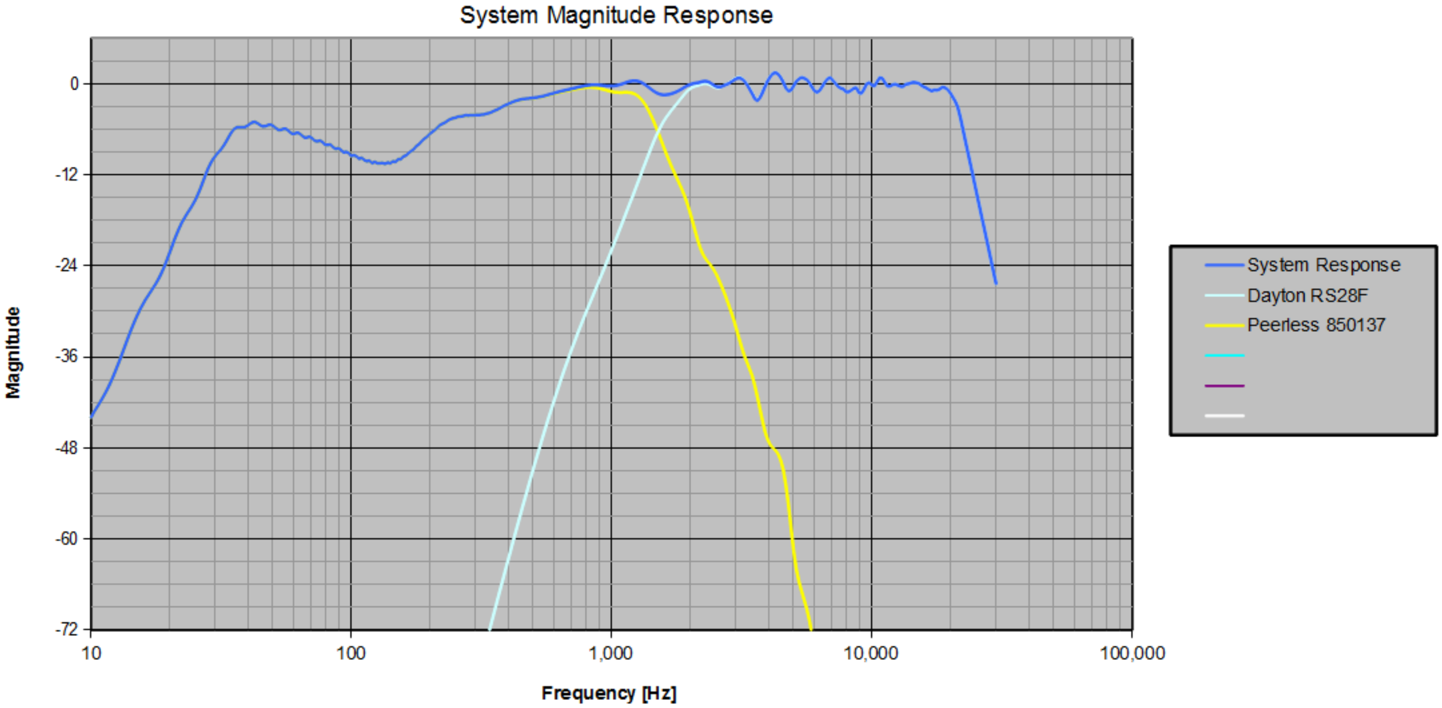


Figure 8: Frequency Response of loudspeaker with modified tweeter filters, modified woofer filters, reversed tweeter polarity and woofer gain reduced by 7 dB.

This is great! Why? Around the crossover point the transition from woofer to tweeter is relatively smooth and there are no abrupt changes, peaks or dips. What we are left to contend with is the large and wide baffle step transition between about 200 Hz and 800 Hz.

Further Flattening the Frequency Response

One way to raise the drooping bass levels is with a first order bass shelving filter (filter type 4). This kind of correction should be applied "globally", meaning to the input to the loudspeaker. This helps to make sure that the phase changes that will come along with the filter's amplitude changes are identically applied to all drivers, preventing any changes in their relative phase angles at the crossover point and therefore leaving unchanged the existing response in that region.

To implement the bass shelving filter, go to the filter table in the SystemInfo worksheet of the SYSTEM workbook. Under Filter 1, enter 4 for the filter type, enter 6 for the gain, and enter 250 for Fop. Press F9 to update if necessary. The plot of system response should now appear as shown in Figure 9, below.

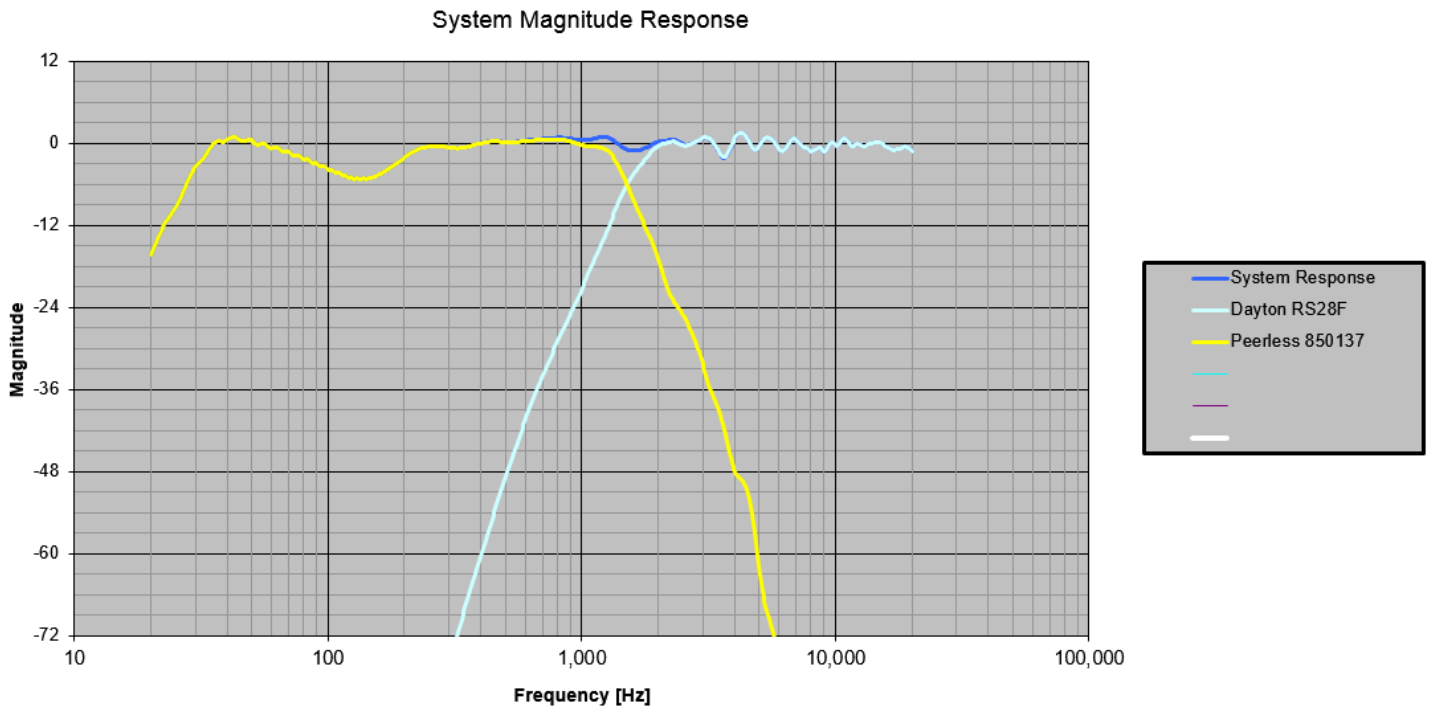


Figure 9: Frequency Response of loudspeaker with modified tweeter filters, modified woofer filters, reversed tweeter polarity, woofer gain reduced by 7 dB, and a bass shelving filter.

The response shown in Figure 9 is approximately ±1.5 dB within flat between 200 Hz and 20k Hz. This is an excellent result, achieved with a simple crossover and baffle step correction, and without EQ.

There is still a pronounced dip around 150 Hz and a peaked response below that. This could probably be solved with EQ, but let's try a different tactic: using a biquadratic (second order) filter instead of the first order bass shelving filter to compensate for the bass droop. For more information on biquadratic filters, see the ACD manual section "Using Filters to Construct Crossovers > Biquadratic Filters".

To implement the biquadratic filter, go to the filter table in the SystemInfo worksheet of the SYSTEM workbook. Under Filter 1, enter 25 for type, 140 for Fop, 1.2 for Qp, 135 for Foz and 0.55 for Qz. Press F9 to update if necessary. The plot of system response should now appear as shown in Figure 10, below.

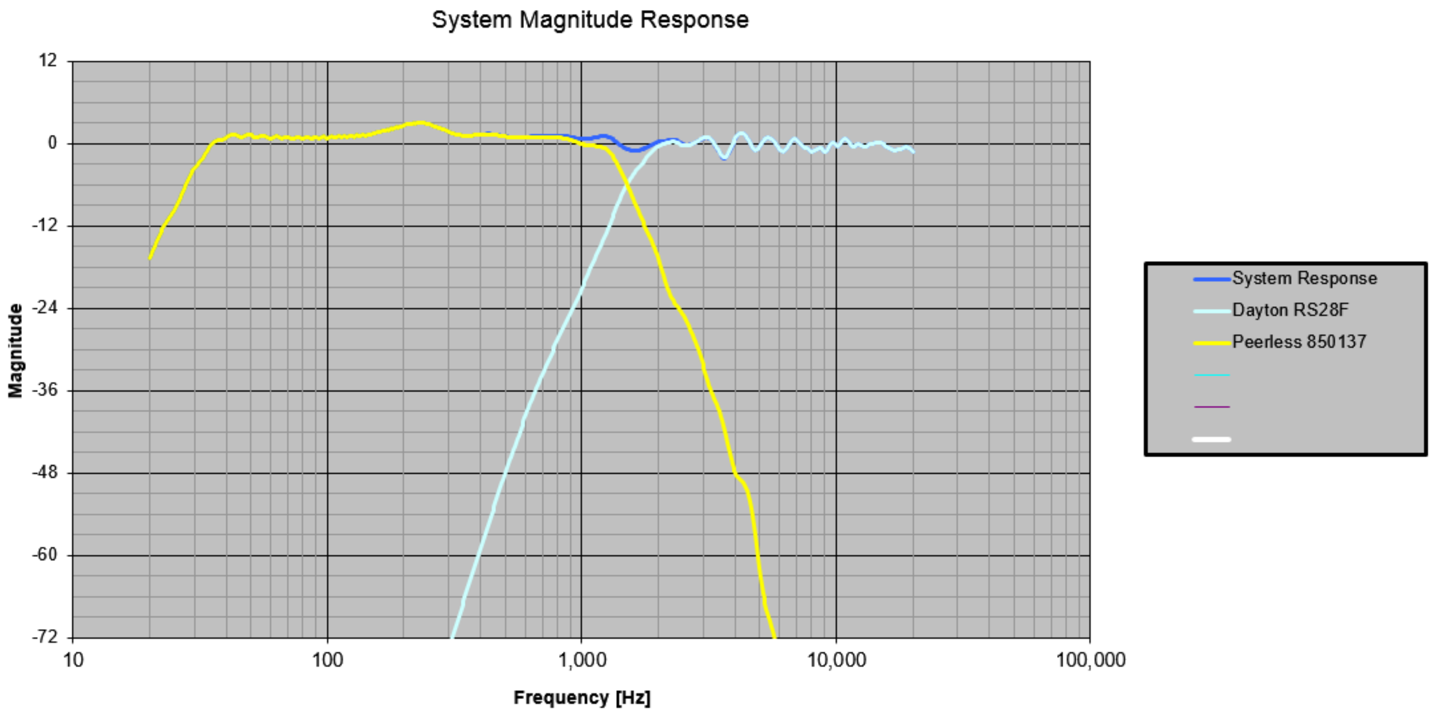
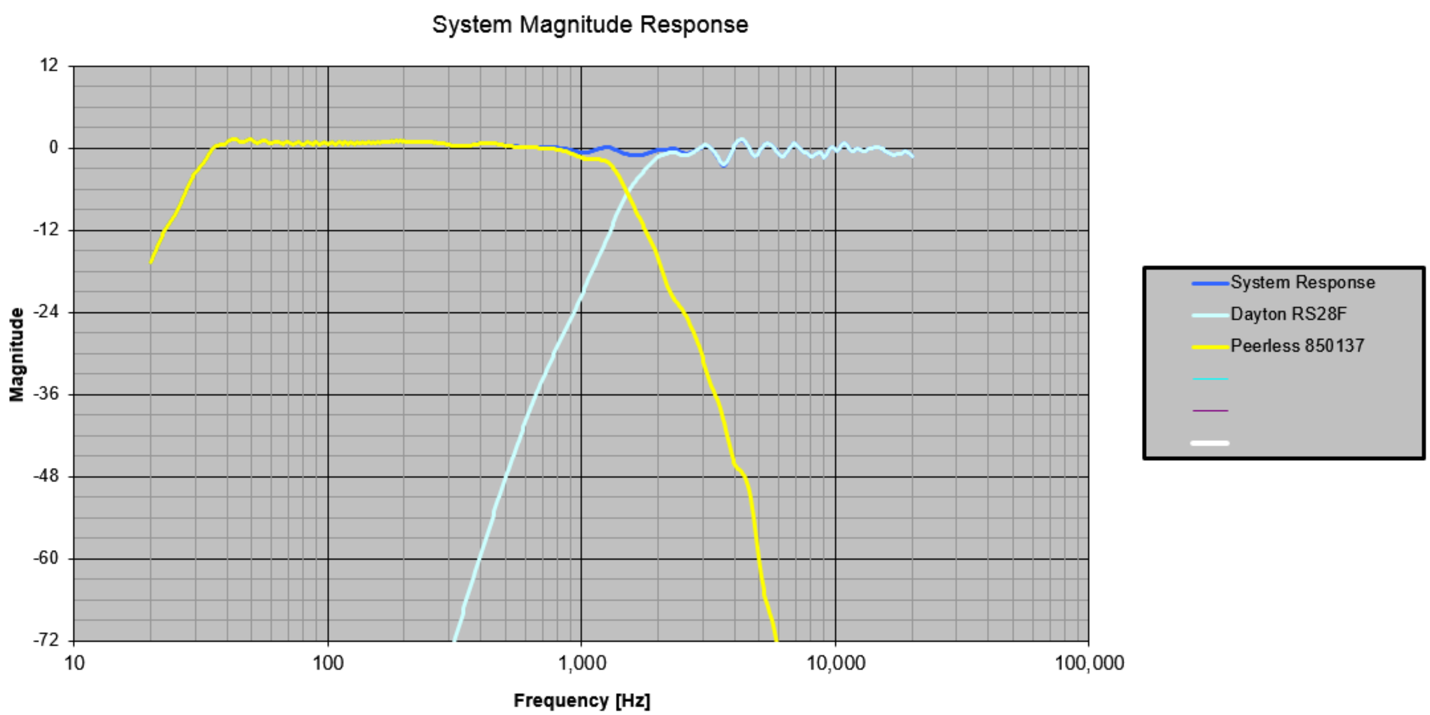


Figure 10: Frequency Response of loudspeaker with modified tweeter filters, modified woofer filters, reversed tweeter polarity, woofer gain reduced by 7 dB, and a biquadratic filter.

We have now improved the response somewhat, however, we have one more round of fixes to apply. We can use EQ to remove the peak around 230Hz and improve the crossover region by reducing the Q value of the woofer and tweeter sections. In the SystemInfo sheet filter table, enter a digital PEQ filter (type 26) for Filter 3 with gain = -2dB and Fop equal to 230 Hz. Press F9 to see the result. Now go to the filter table in the woofer's DriverInfo sheet. Change the Q value of the second low pass filter from 1 to 0.8 and change the Fop for that filter to 1400Hz. Finally, go to the filter table in the tweeter's DriverInfo sheet. Change the Q value of the second high pass filter from 1 to 0.9. Return to the SystemInfo sheet of the System Response workbook and press 9 to see the result of these changes. The system response plot should look like this:



The system response is now approximately +/-1.5 dB from 50Hz to 20kHz, on axis. Nice job!

It’s very likely that there are other crossover formulations that could result in a system response that is equally good but use a different set of filters. It’s up to the designer to decide which is appropriate, and of course listening tests and system response frequency measurements are also helpful and instructive. Keep in mind that developing the crossover is a manual, iterative process and keep at it! After going through the process a few times you will come to appreciate the flexibility of being able to fully customize the filter parameters via the filter table.

Examining the Phase Angle between Two Drivers

Previously we employed the heuristic that drivers will add to an SPL that is 6 dB above the point at which the driver responses intersect at the crossover point to indicate that they were operating in phase. It is often very useful to look at the phase relationship between a pair of drivers in more detail to check if the phase alignment is good over a wider range, and to see how changes to the crossover filters are influencing the phase alignment.

There is an ACD extension that clearly shows the relative phase angle for any two drivers called the TWO-DRIVER PHASE TRACKING extension. It’s strongly suggested that the extension be used to monitor the relative phase angle when designing crossovers instead of simply relying on the addition at the crossover point. The extension provides clear information that is very useful for keeping the phase alignment well controlled by your crossover and is a helpful guide for improving phase alignment. The two-driver phase tracking extension is available for download at the ACD web site. Let’s use it to look at our current crossover between woofer and tweeter and see how we have done.

Download the phase tracking extension spreadsheet. Follow the instructions on the first sheet that explain how to link the complex response of each of the two drivers into the spreadsheet. Link the tweeter into driver_1 and the woofer into driver_2. Edit cells C6 and C7 to set driver 1 name to “tweeter” and driver 2 name to “woofer”. Recalculate the worksheet by pressing F9. The plots below should look something like this:

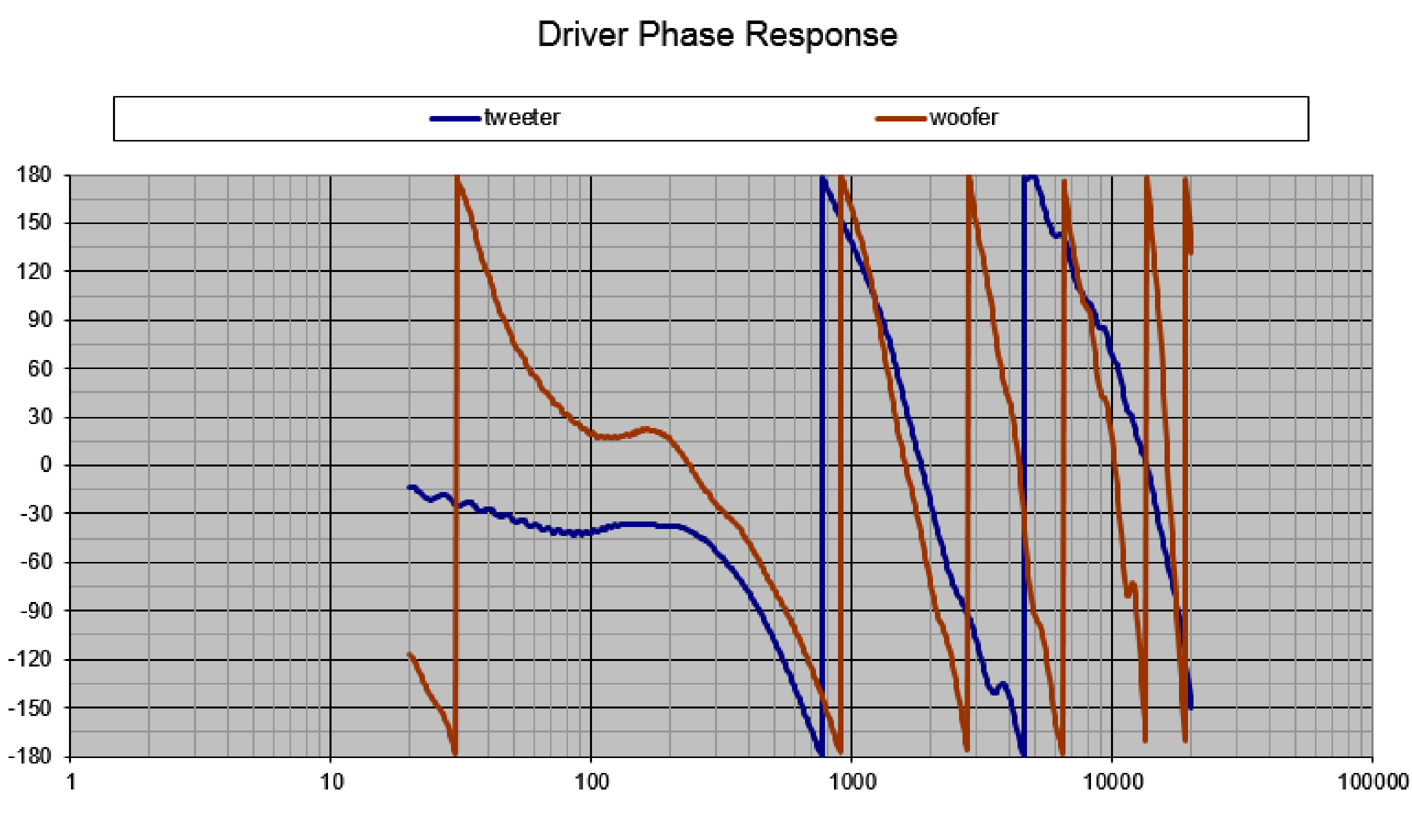


Figure 11: The phase responses of the two drivers linked into the TWO-DRIVER PHASE TRACKING extension.

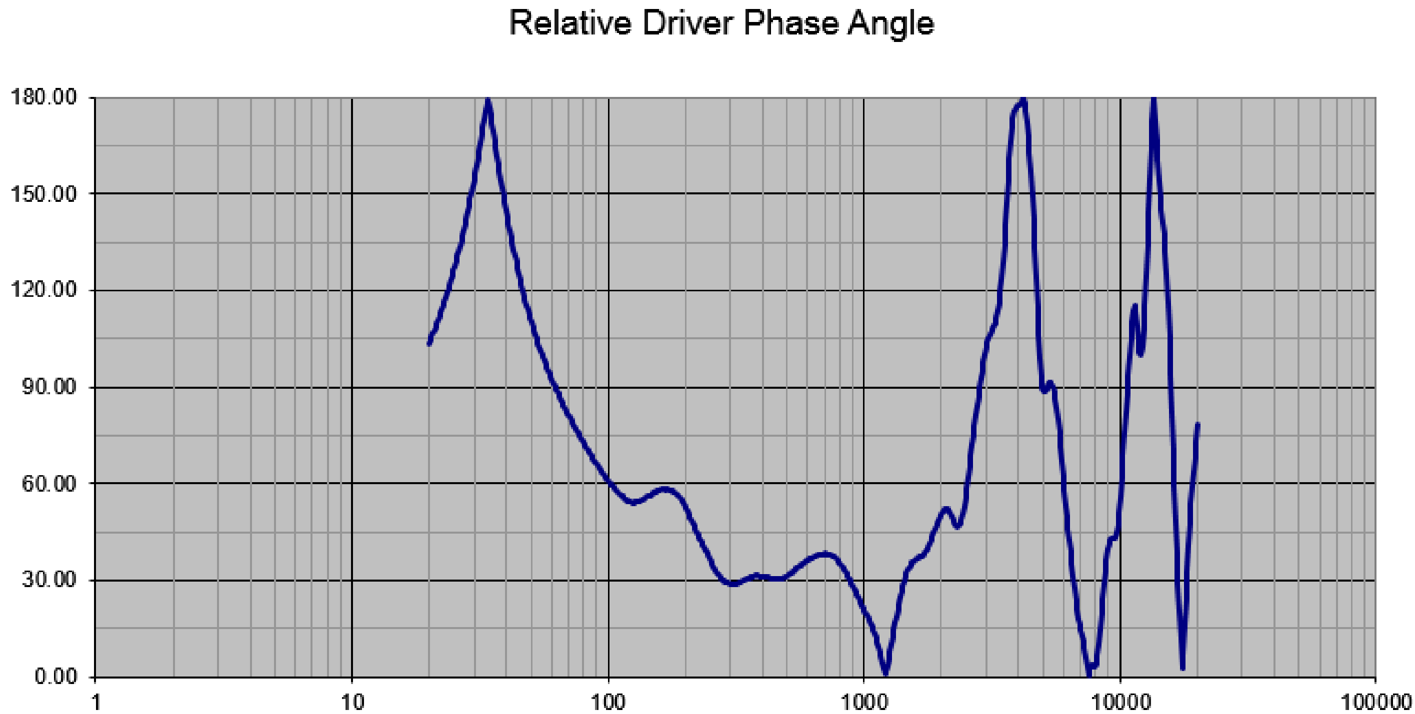


Figure 12: The relative phase angle between the two drivers linked into the TWO-DRIVER PHASE TRACKING extension.

We will be using both plots to determine what phase corrections might be used to improve the phase alignment around the crossover point between these two drivers. The goal is to maintain a low relative phase angle around the effective crossover point which, for this loudspeaker, is about 1500Hz. We won't likely be able to keep the drivers exactly in phase, and here a "low" relative phase angle means below 30 degrees, the lower the better. Keeping the phase in close alignment with in one-half to one octave below and above the crossover point will help to insure that the frequency response in the crossover region will remain stable when the listening location moves off axis from directly in front of the loudspeaker.

Evaluating the relative phase and determining how to proceed

Looking at Figure 12 we can see that the phase angle barely manages to meet our criteria between 1500Hz and 750Hz (one octave below the crossover point) but exceeds this between 1500Hz and 3000Hz (one octave above the crossover point). We will look a little more closely at the Figure 11 to find out what is going on, but first let's talk about the phase in general.

In general the phase response is a monotonic (linearly decreasing) quantity. It is normally plotted with a scale running between 180 degrees and -180 degrees and when the phase exceeds either of these limits it is "wrapped" back onto the plot. This is an artificial construction – the actual phase value can be many thousands of degrees (below zero) at high frequencies. Looking at Figure 11 you can see that at lower frequencies (50Hz-200Hz) the phase is generally trending down with a certain slope. The slope starts to increase around 200Hz and after wrapping in the plot at about 900Hz the slope again steepens downwards above 1000Hz. This general trend in the phase is typical. The drivers have their own phase response that is a result of their bandpass character. The crossover filters also cause additional phase wrapping, both highpass filters and lowpass filters. Bandlimited filters like EQ cause local phase perturbations but their effect returns to zero away from the band center frequency. The more actors on that phase that are present, the more the slope (or derivative) of the phase will steepen. In order to get the phase of these two drivers aligned, we need to bring the phase of each driver onto the same slope, and get them to overlap as much as possible.

Since we have already designed a relatively flat response, we don't want to impact it so in this case we will try approaches that only change the phase response. There are several ways to do this. One approach that is commonly used in the passive crossover community is to use an additional highpass or lowpass filter to add additional phase lag (increasing phase lag = increasing the downturn or slope of the phase angle). Active filters allow the design to easily apply one of more first or second order all-pass filters. An all-pass filters is one that has a flat frequency response and a frequency-dependent phase response. Additionally, "digital delay" can be used. Digital delay is a frequency independent delay, whereas the all-pass filter has a delay that falls back to zero at high frequencies and with a shape that can be controlled by the "Q" of the all-pass filter (for second order).

There is not a complete and straightforward strategy for making changes to the phase response. It takes experience and an understanding of how a certain filter will change the phase, and some trial and error. In this case the modification that were chosen will simply be described and the results presented.

An Example of Phase-Manipulation

Return the tweeter's Driver Response workbook, to the DriverInfo sheet and find cell B32 where you can enter the digital delay in milliseconds. Enter the value 0.12 milliseconds. Next, we will enter a new filter in the filter table. Enter a first order all-pass filter (type 3) with a corner frequency (Fop) of 700 Hz. Finally, change the polarity of the reversed phase filter (filter one) from -1 (reversed phase) to 1 (normal phase). Recalculate the workbooks by pressing F9.

Returning to the driver phase tracking extension workbook, we see the following:

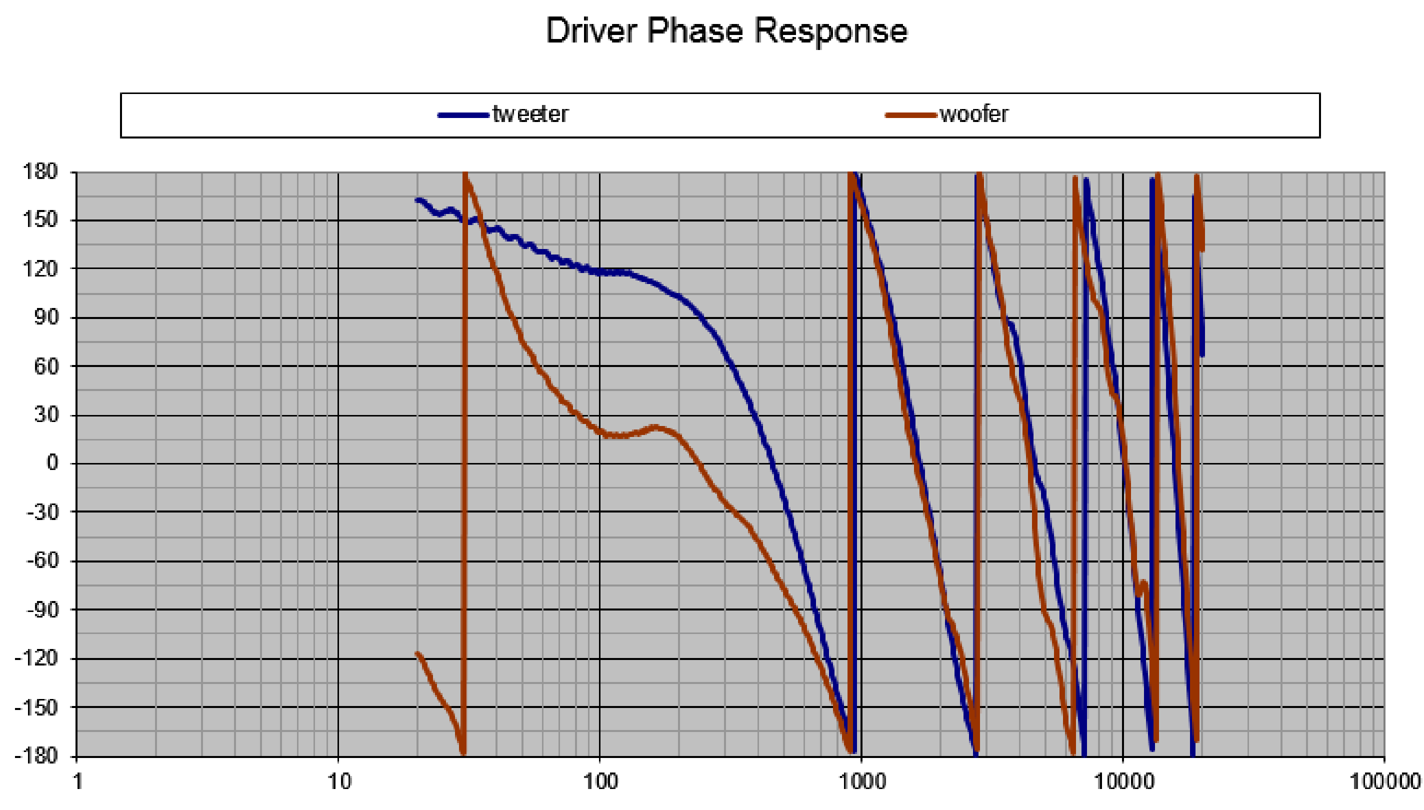


Figure 13: The phase responses of the two drivers including the phase manipulation filters.

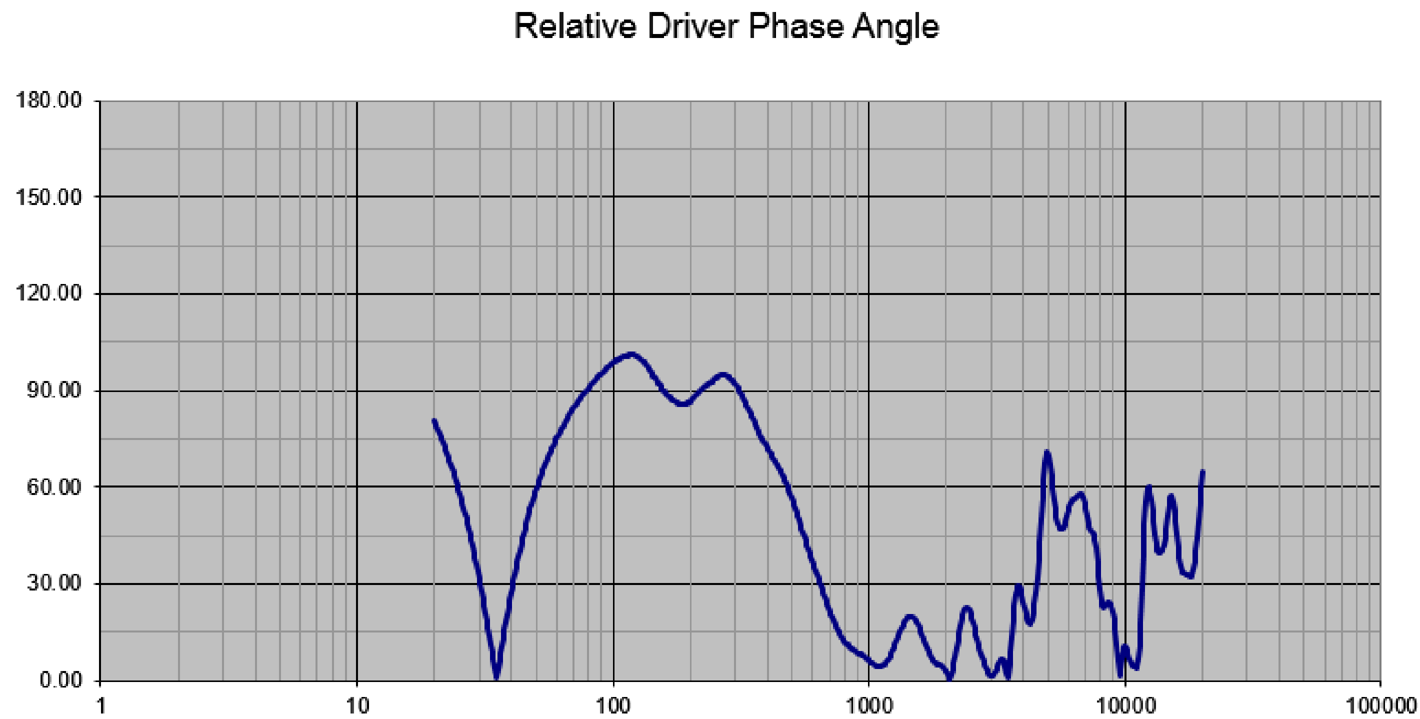


Figure 14: The relative phase angle between the two drivers including the phase manipulation filters.

By comparing Figure 14 and Figure 12 it is clear that the relative phase angle for this pair of drivers has been improved around the crossover point (1500Hz). The relative phase angle is now less than 15 degrees from 750Hz to 3kHz. This has especially improved the relative phase above 1500Hz when compared to the same crossover without the phase manipulation.

Since no filters that change the amplitude response were used and since the phase was already relatively low the loudspeaker system SPL has not changed appreciably, as evidenced by Figure 15, below.

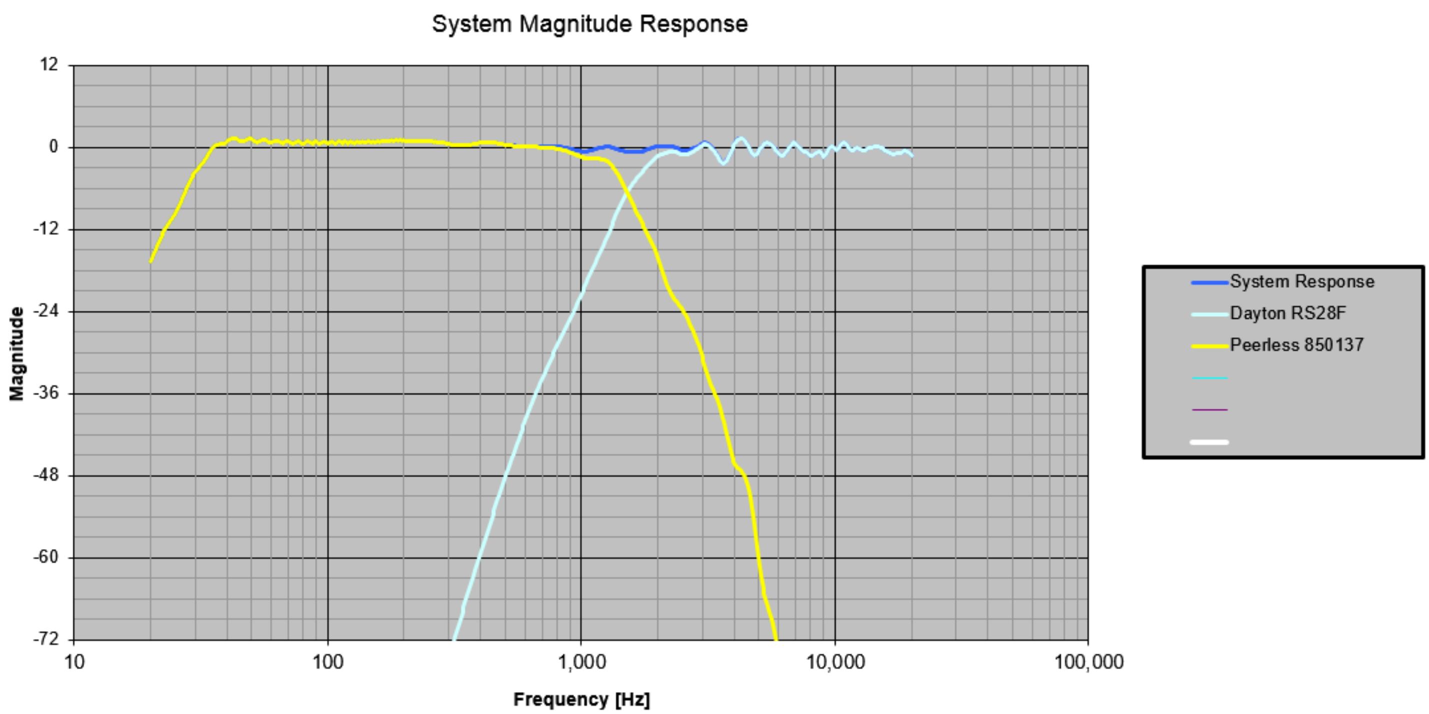


Figure 10: Frequency Response of loudspeaker including the phase manipulation filters.

Improving the phase relationship has not made any obvious improvements in the system frequency response, so why bother? The reason is that we are only looking at the on-axis response of the loudspeaker. When the relative phase angle is high (e.g. 45-90 degrees) on axis, the changes to the relative phase brought on by moving off-axis can push the relative phase angle past 90 degrees and deconstructive interference will arise, meaning that a null will begin to develop. This will change the sound character on that axis, and may influence the soundfield for the listener via the reflected "room" response of the loudspeaker. It is a good idea to keep the on-axis phase as well-aligned in the crossover regions as possible to minimize these effects. This type of theme will be covered in more detail in the multi-axis crossover design tutorial for ACD-L.

There are many ways to manipulate the phase and you may need to experiment with several approaches before you arrive at a satisfactory combination. The above example was arrived at by experimentation and other approaches could be just as good or better. Thanks to the power and versatility of DSP processing the designer has complete freedom to choose from a variety of approaches.

Collecting the information on the crossover from the loudspeaker model

When it is time to implement the crossover, collect all the information on the filters in terms of the ACDf and mTAP LADSPA plugins in the following way:

Find the LADSPA string for filters applied to the woofer in the LADSPA_INFO sheet of the woofer workbook. The text string will beginning with "-el:ACDf…" and is found in cell A5. Copy the text and paste it into where you can implement it using ecasound.

Likewise, find the LADSPA string for filters applied to the tweeter in the LADSPA_INFO sheet of the tweeter workbook. As before, the text string will beginning with "-el:ACDf…" and is found in cell A5. Copy the text and paste it into where you can implement it using ecasound.

Finally, find the LADSPA string for filters applied to the system input in the LADSPA_INFO sheet of the system workbook. There are potentially two text strings of interest here. One text string begins with "-el:ACDf…" is found in cell A5. The other text string (for the digital filters) may or may not be needed. It's located in cell A16. If it begins with the text "-el:mTAP…" copy it, and the text for the ACDf filters and paste it into where you can implement it using ecasound.

For the crossover that has been developed in this tutorial, the text string are:

Tweeter:

```
-el:ACDf,22,1,0,2000,1,1,1 -el:ACDf,22,1,0,2000,0.9,1,1 -el:ACDf,3,1,0,700,1,1,1
```

Woofer

```
-el:ACDf,21,1,-7,1250,1,1,1 -el:ACDf,21,1,0,1400,0.8,1,1
```

System:

```
-el:ACDf,4,1,6,250,1,1,1 -el:ACDf,25,1,0,140,1.2,135,0.55 -el:ACDf,26,1,-2,230,2,1,1
-el:mTAP,0.12,0
```

Recap and Summary

Let’s review what we have accomplished - you have learned how to import FRD data into the driver spreadsheets, determine the acoustic delay, enter some filters to build a crossover, and then tweak the filter Q and frequency to manipulate the driver and system frequency response. Finally, the phase response was improved so that the performance on and off-axis could be maximized.

Once you are comfortable with the general process you can begin to enjoy both the challenge and the fun of crossover development – you can try different combinations of filter Q, filter frequency, etc. and experiment with your own designs. With active crossovers, you are completely free to manipulate these parameters at will without any regard for the driver’s electrical impedance and you can focus on the performance of the loudspeaker.