

## Speaker Crossover Analysis

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### Introduction

A Vector Network Analyzer (VNA) is one of the most important aids for analog designs. It can provide accurate information about active and passive network performance in the frequency domain, such as frequency response, phase response, impulse response and so on. Designers heavily rely on these measurement results to locate design problems and to evaluate network performance.

This application note discusses how to measure the impedance of loudspeakers as well as how to measure frequency response of audio crossovers using the SA/RA Series Frequency Response Analyzer. After a short introduction to the measurements this document will show how to configure the Frequency Response Analyzer and how to perform the measurements.

### Notes:

1. All measurements in this application note have been performed with the SA/RA Series Frequency Response Analyzer software Suite V5.50.

### Speakers

Physics sets the limits for audio reproduction systems and compromises have to be made. As no loudspeaker driver can reproduce all the audible frequencies from 20 Hz to 20 kHz without amplitude reduction, splitting the spectrum for multiple drivers is required. Loudspeaker crossovers are used to accomplish this, but at the same time crossovers introduce several problems. Some have more than others. The crossover is an electronic filter, which is typically passive and mounted inside the speaker enclosure. In this Application Note, I have concentrated on a two-way crossover network.

An ideal crossover would filter exactly the defined range of frequencies to the woofer and respectively to the tweeter, so that no overlap occurs between the drivers. It would, as well, keep the filtered output signals from the woofer and tweeter intact, in terms of magnitude and phase. In reality, such filter is not

possible due to physical limitations of components. The schematic shown in Figure 1, is the crossover used in the speakers tested.

In a loudspeaker, the transfer function of a crossover filter consists of the sum of low-pass and high-pass filters' transfer functions in a two-driver case. It must be remembered that the total reproduction consists of the transfer functions of both the crossover filter and the loudspeaker drivers, although here the crossover filter is only discussed.

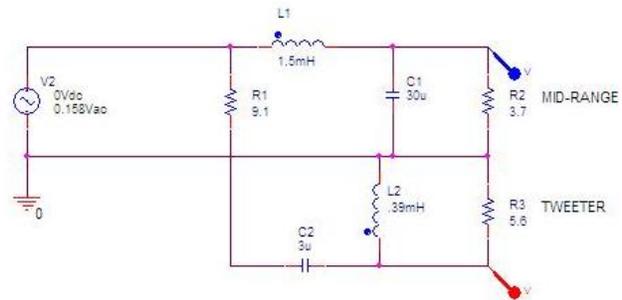


Figure 1  
Crossover Used in Testing

The filter's transfer function is written by the following equation:

$$H(s) = H(s)_L + H(s)_H$$

Where  $H(s)_L$  and  $H(s)_H$  are the transfer functions of the low-pass and high-pass sub-filters. In order to achieve a good response on the listening axis, the drivers are time aligned for coplanar radiation, otherwise, there is a lobe error (tilting) in the loudspeaker's radiation pattern towards the lagging driver, which is outside this discussion.

Figure 2 shows the magnitude response of a simulation of the crossover used in these speakers. The magnitude response can be considered the most important parameter in crossover design. Where high-pass and low-pass signals cross over, they overlap and affect each other's reproduction accuracy by interference. How much, depends on the phase relation between the speakers.

When the woofer and tweeter are both contributing to the reproduction in the crossover frequency region, being in the same phase means that they boost each other, or cancel each other when in the opposite phase. In addition, their mutual phase through the whole frequency range is of importance.

The final design of a good loudspeaker means the whole transfer function of the system, not just the crossover. In practice, the properties and desired parameters of a crossover depend on the driver's physical properties, and that of the enclosure.

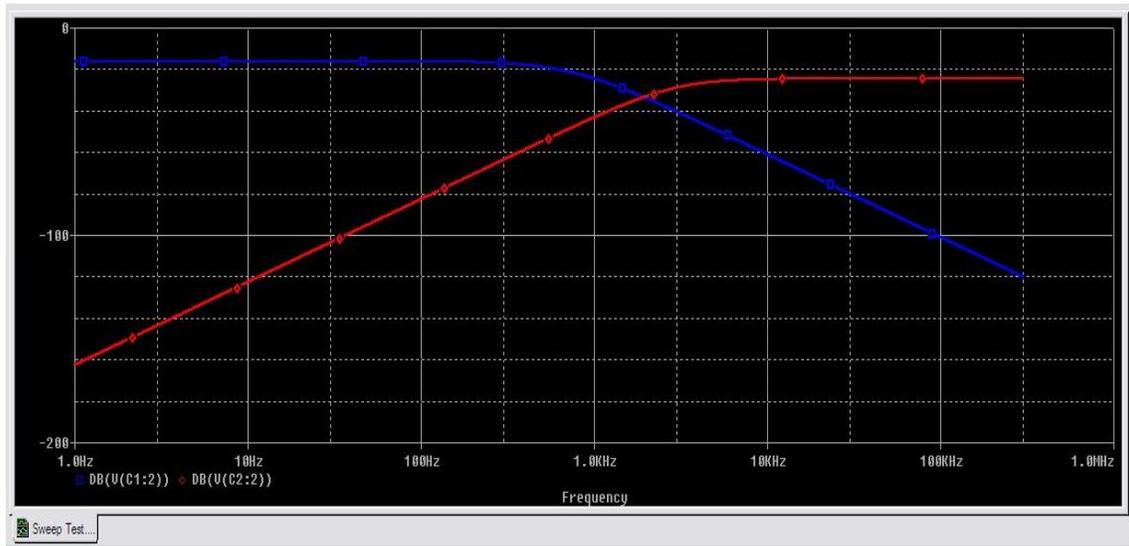


Figure 2  
Simulation of Crossover in Figure 1

It is safe, for now, to assume the manufacturer of the loudspeakers used in this testing have followed the design practices discussed above in developing this crossover.

## Speaker Details

The measurements discussed in this document were performed on a real full-range passive bookshelf loudspeaker (the manufacturer shall remain nameless). These loudspeakers are a high-end consumer product and are owned by the author of this Application Note. The speakers consists of a tweeter and a mid-range / woofer as well as a crossover. Both speakers are installed in the same enclosure along with the crossover.

## Measurements

The following measurements are discussed in this application note:

- Impedance measurement of loudspeakers.
- Impedance at the input to the crossover.
- Frequency Response of each path of the speaker crossover.

## Impedance Measurement

### Impedance Setup

One of the most difficult measurements to make in audio is impedance. Whether measuring the impedance of an individual component or a complete network, the Frequency Response Analyzer, makes this a simple task.

For the input impedance measurement we perform a logarithmic frequency sweep from 10 Hz to 40 kHz and use an output level of 0 dBm such that the sound of the loudspeakers during the measurement is not too loud and so that we do not overload the analyzer inputs. The **Input Over Voltage** bargraphs in the **Sweep Parameters** tab on the virtual front panel of the analyzer indicate an input level that is too high by displaying a red bar. It is important that there are no red bars, which indicates clipping, during a sweep. If clipping occurs, simply decrease the level and re-run the test.

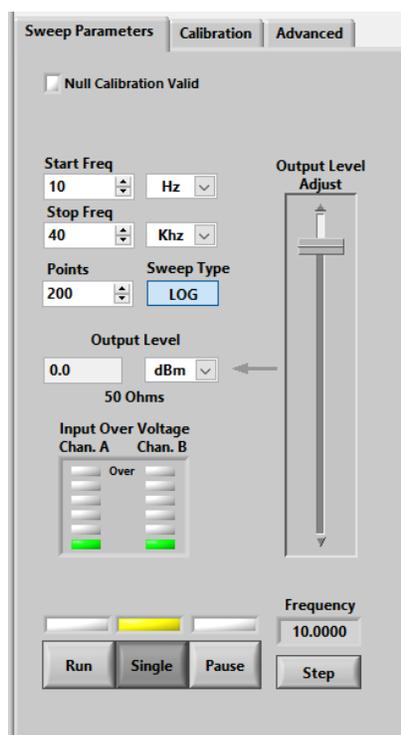


Figure 3  
Sweep Parameters Tab

We set the number of points to 200 in order to speed-up the frequency sweep process while still delivering enough resolution. Under the **Advanced** tab, we set the IF Bandwidth to 5 Hz, which is below the lowest frequency in the scan. Changing the IF Bandwidth helps to reduce noise while making the sweep take longer due to the number of calculations.

The image in Figure 5 shows the connection of the Frequency Response Analyzer (FRA) to the speaker terminals.

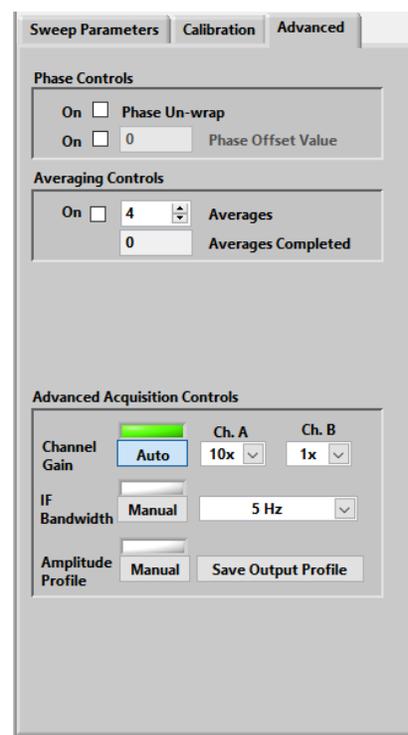


Figure 4  
Advanced Tab

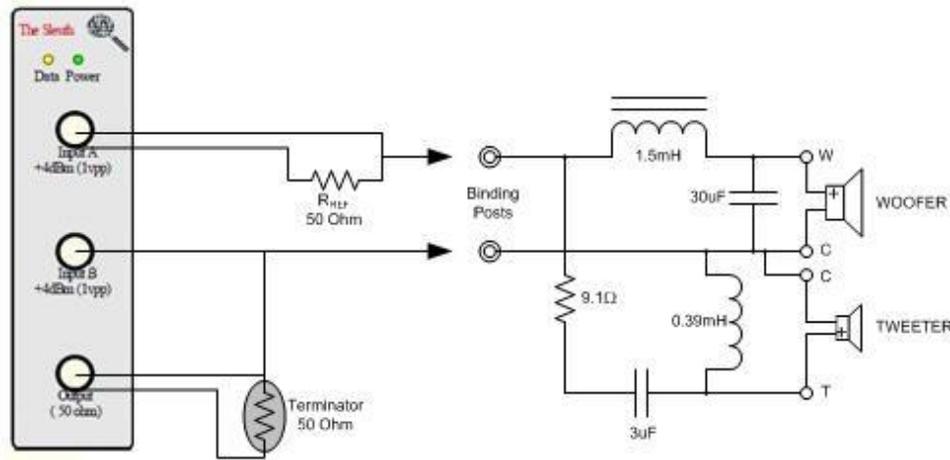


Figure 5  
 Connection for measuring Impedance

Reference resistor,  $R_{REF}$ , in Figure 5 is used to sense the current through the network. The value of the reference resistor is entered into the **Calibration** tab on the virtual front panel of the analyzer.

## Input Impedance

Once everything is connected as shown in Figure 5, the Input impedance test can be run by clicking on the “**Run**” button. As the test progresses, you will see the graph being drawn on the screen. When the graph is complete, the numbers below the graph will be updated, see Figure 6.

At the end of this test, we positioned Cursor 1 (C1) at the low frequency peak. In the C1 column under the graph, we can read the impedance and frequency where the cursor is positioned. In this case, 57.575 Hz and 25.19 ohms. By moving the cursor the impedance at any frequency can be found. The true impedance of this 8 ohm speaker is about 4.8 ohms at 20 Hz and reaches 142 ohms at 20 KHz.

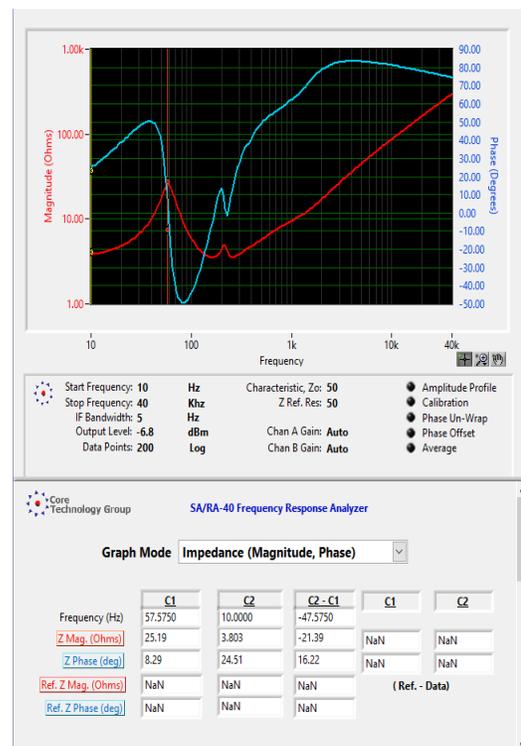


Figure 6  
 Speaker Input Impedance

Keep in mind, this measurement includes all the components in the system including both the woofer and tweeter along with the crossover. A word of warning is worthwhile here. **Never** power-up an amplifier connected to a crossover network with the drivers disconnected. It may be tempting during testing, but at a frequency equal to the series resonant frequency of the inductor and capacitor, the network may present an almost dead short circuit to the amplifier (depending on the filter type), which could damage the amplifier, crossover or both.

## Woofer Impedance

One area where measurement is essential when designing passive crossovers, is the loudspeaker driver itself. There is usually very little information in the manufacturer's data that will prepare you for the behavior of a loudspeaker / crossover network combination, and these data are usually derived empirically.

In almost every case, the crossover frequency selected for the woofer and midrange driver will be at a frequency where the voice coil inductance peaks. As frequency increases, the effect of the voice coil inductance increases the driver's impedance, and this plays havoc with the crossover's performance.

Because the voice coil is surrounded by conductive metal (steel), its inductance is not linear with frequency. This creates a lossy inductor, and as such it cannot actually achieve the 6dB/ octave (20dB/ decade) impedance rise that one would normally expect. The actual rise varies from one driver to the next, and cannot be simulated in general terms - it must be measured.

Using a Frequency Response Analyzer, the impedance of each driver can be individually tested. Simply connect the speaker, without the crossover, directly across the wires from the Frequency Response Analyzer. The Woofer impedance and phase are shown in Figure 7. The graph looks a lot like low frequency portion of the system impedance in Figure 6, which indicates the woofer impedance is effecting the crossover; which it should.

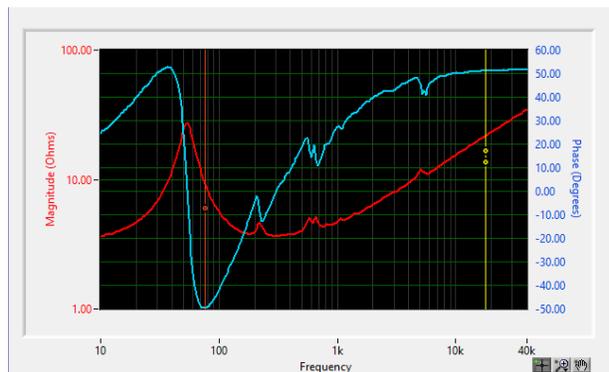


Figure 7  
Woofer Impedance

**Note:** The impedance of any single component or any network may be tested with this setup. With reactive components, such as capacitors and inductors, we can use the magnitude and phase to calculate reactance of the component. The graph can also be changed to “**Impedance (Real, Imaginary)**” and the reactance can be seen directly as “**Z Img**”. For more details refer to Application Note (AN-6) for more information on Measuring Inductors and Capacitors.

## Tweeter Impedance

Unfortunately, it is extremely difficult to get the required details for most tweeters. The resonance is almost always quoted, but most of the time it is difficult to find the voice coil inductance, which would enable one to accurately calculate the required crossover network.

The Q of the crossover circuit must be the same as the resonance Q, or it will simply form a sharp notch in the middle of the resonance peak (Q too high) or a broad notch that spans the resonance (Q too low). The traditional way to measure Q is to measure the bandwidth between the -3dB frequencies, then divide the resonant frequency by the bandwidth. However, a tiny measurement error will cause a large final calculation error. Fortunately, this is rather easy to measure accurately with the SA/RA Series Frequency Response Analyzer. Further discussion in this area leads us into the Thiele – Small Parameters which is outside the topic of this application note.

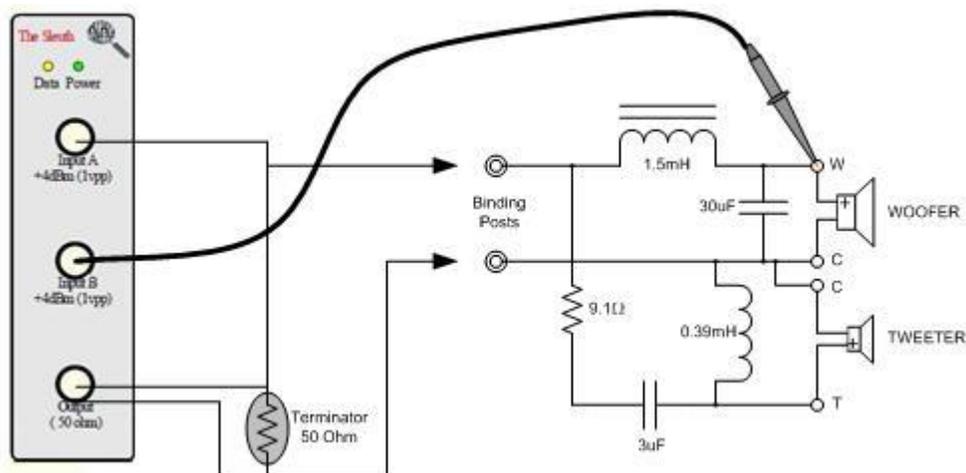


Figure 8  
 Frequency Response Setup

## Frequency Response Measurement

To measure frequency response of a network requires changing the connections at the Frequency Response Analyzer as shown in Figure 8.

## Frequency Response Setup

When measuring frequency response of an active or passive circuit, connect the output of the Frequency Response Analyzer across the input of the device as you would any signal generator. We select Bode (Phase, Magnitude) as the graph mode. No changes are required to the **Sweep Parameters** or **Advanced** settings unless the test requires a different frequency range. For our purposes, the frequency range will remain 10 Hz to 40 KHz. For these tests, Input A is used to monitor the frequency input to the network and Input B monitors the device output.

**NOTE:** Should Input A and Input B be reversed, the resulting waveforms will be reversed vertically.

## Woofer Frequency Response

With the probe from Input B connected to the woofer positive output of the crossover, we can see the frequency response through the crossover and across the woofer in Figure 9. The Bode graph shows the attenuation of the input signal in dB across the frequency spectrum. It looks just like you might expect a crossover to work.

We can move a cursor to the  $-3$  dB point and directly read the frequency, as shown in Figure 9. In this test, we were unable to get to  $-3$  dB because there were not enough sample points in the test we performed. Should this occur, simply increase the number of **Points** in the **Sweep Parameters** tab and re-run the test.

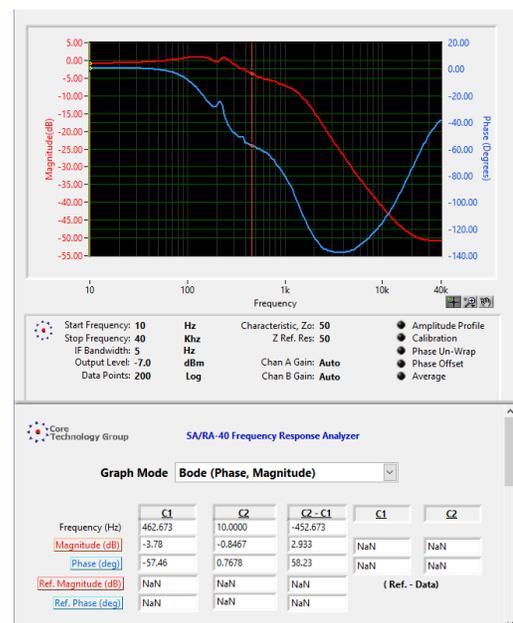


Figure 9  
Woofer Frequency Response

## Tweeter Frequency Response

To measure the Tweeter frequency response, simply move the probe to the positive tweeter terminal. In Figure 10, the frequency response of the tweeter can be seen. Here we can measure the -3 dB point at 11 KHz.

Unlike the woofer with its smooth roll-off, the tweeter frequency response has several humps below the crossover frequency. The peak of these humps are at about -38 dB, which this manufacturer determined was enough attenuation for their speaker.

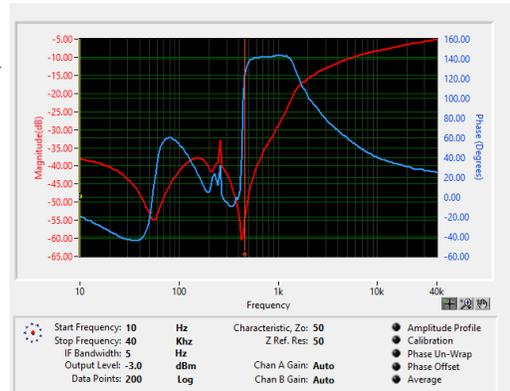


Figure 10  
Tweeter Frequency Response



Figure 11  
Overlaid Crossover Waveforms

By making the tweeter frequency response the Reference (**Data / Current --> Reference**) and running the woofer test again, we can see both response curves simultaneously in Figure 11.

You can clearly see the crossover frequency (Red lines) is at 2 KHz. You can also see a bump in the tweeter frequency response at about 150 Hz. There is a 46.6 degree phase shift between the speakers at this frequency indicated by Cursor 2 (Yellow). To find the resulting output level at this frequency requires converting the db levels back to voltage as follows:

$$V = 10^{\frac{dB}{20}}$$

Then perform vector math on the two phasors: 1.099 V ( $V_1$ ) @  $-21.33^\circ$  ( $\Phi_1$ ) and 0.013 V ( $V_2$ ) @  $25.35^\circ$  ( $\Phi_2$ ).

$$Real_T = (V_1 \cos \Phi_1) + (V_2 \cos \Phi_2)$$

$$Imaginary_T = (V_1 \sin \Phi_1) + (V_2 \sin \Phi_2)$$

Now that both the real and imaginary values have been found the magnitude of voltage,  $V_T$  is determined by using Pythagoras's Theorem for a  $90^\circ$  triangle as follows:

$$V_T = \sqrt{(Real)^2 + (Imaginary)^2}$$

Once we have the total we convert it back to dB as follows:

$$dB = 20 \log(V_T)$$

Using Excel for the calculations, the spreadsheet looks like this:

|                              | From FRA                     | dB → Volts     | Calculations |          |
|------------------------------|------------------------------|----------------|--------------|----------|
| <b>Magnitude<sub>1</sub></b> | 0.8186 dB                    | 1.098829 $V_1$ | Real         | -0.86729 |
| <b><math>\Phi_1</math></b>   | -21.33 Deg                   |                | Imaginary    | -0.67471 |
|                              |                              |                |              |          |
| <b>Magnitude<sub>2</sub></b> | -37.94 dB                    | 0.012677 $V_2$ | Real         | 0.012379 |
| <b><math>\Phi_2</math></b>   | 25.35 Deg                    |                | Imaginary    | 0.002732 |
|                              |                              |                |              |          |
|                              | <b>Real<sub>T</sub></b>      | -0.85491 V     |              |          |
|                              | <b>Imaginary<sub>T</sub></b> | -0.67197 V     |              |          |
|                              |                              |                |              |          |
|                              | <b><math>V_T</math></b>      | 1.087394 V     |              |          |
|                              |                              |                |              |          |
|                              | <b>Converted to dB</b>       | 0.727741 dB    |              |          |
|                              |                              |                |              |          |

Figure 12  
Excel Spreadsheet of Waveform addition

The resulting waveform at 150.159 Hz is about 0.73 dB which reduces the woofer output by about 0.091 dB. Of course, room acoustics will play a much larger role in the final frequency response of the speaker.

## Summary

This Application Note has demonstrated how to use the SA/RA Series Frequency Response Analyzer to measure the impedance and frequency response of crossovers and speakers. When designing crossovers, engineers perform calculations and make simulations regarding crossover performance. These calculations can be verified and the data gathered can be used by the engineers to improve their simulation models.

In addition, speaker performance can be quickly verified in production against a saved test, to see how manufacturing variations and component tolerances are effecting circuit performance.

In short, the SA/RA Series Frequency Response Analyzer is an essential tool for engineers to verify their designs and to insure component variations do not render performance outside product specifications.

For additional Information on how to measure the characteristics of audio amplifiers can be found in application note "AN-9 Audio Circuit Testing".