Design and Construction of a High-Fidelity Audio Loudspeaker System

By

Bradley Okresik

ECE 345, SENIOR DESIGN PROJECT
FALL 2002

TA: Chirantan Mukhopad

12/7/02

Project No. 33

ABSTRACT

A three way audio loudspeaker system is designed and constructed with an emphasis on achieving excellent transient behavior. The drivers are carefully chosen and purchased commercially; T/S parameters are used to simulate the drivers' response in various box sizes. A wooden box is constructed for each driver including internal bracing, steel stiffening supports, and damping clay. During the design of the enclosures many acoustic effects are considered such as vibration modes, diffraction, baffle step, and flush mounting of the drivers. Impedance and acoustic response is measured from 10Hz – 20kHz for all six drivers mounted in their enclosures. The measured data is used to design and simulate several crossover networks. 1st and 3rd order Butterworth filters are constructed with crossover frequencies of 450 Hz and 2500 Hz. Switches allow 'on the fly' changing between 1st-1st, 1st-3rd, 3rd-1st, and 3rd-3rd order crossovers. All impedance correction circuits can also be switched in or out of the circuit.

TABLE OF CONTENTS

1. INTRODUCTION

A loudspeaker system is designed and constructed utilizing three drivers, each operating over a different range of the audio spectrum (20Hz- 20kHz). A block diagram of the system is included in Fig. 1.

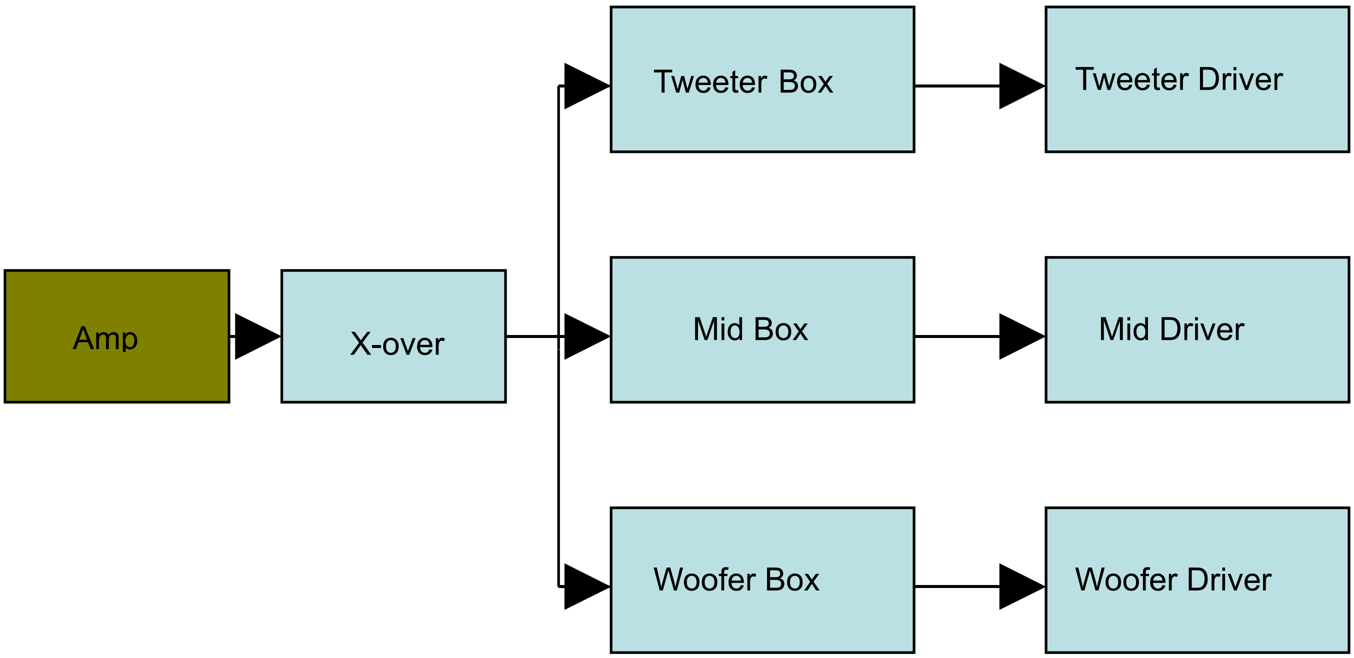


Fig. 1. Block diagram of the loudspeaker system.

This audio system includes the electrical crossover network, the enclosures, and the acoustic drivers. All three of these aspects will significantly contribute to the characteristics of the entire system frequency response. The general design involves separating the drivers into three different enclosures with a passive crossover located outside of these boxes.

1.1 Purpose and Design Goals

The purpose is to develop a high performance loudspeaker that can accurately reproduce an audio recording. An awe-inspiring aesthetic is equally as important as achieving a desired flat frequency magnitude response (±1dB) with a minimum amount of phase shift and group delay. Excellent transient response is a very important aspect of the design. In order to yield such a near perfect response, the system must have a low quality factor (less than 0.707), minimize undesired effects due to diffraction, and the crossover design must compensate for any irregularities in the impedance and acoustic response of the driver/box combination. This necessitates the use of low order crossovers and low Q driver/box alignments.

1.2 Driver Selection

Selecting appropriate drivers is a difficult task. The general design of the entire system must be known and considered when the drivers are chosen. The electro-mechanical characteristics of each driver have to coincide with the size of the box and the general type of crossover.

Thiel and Small [1] have provided theory and equations that characterize the response of a driver when placed in an enclosure. Manufactures publish measured T/S parameters for their drivers. These T/S parameters describe the electro-mechanical characteristics of the driver. These values and the equations below [2] were used with an MS Excel spreadsheet to simulate box volume, system Q, and low frequency behavior of all possible bass and midrange drivers.

V_{as} = Equivalent air compliance of the driver's suspension system

Q_{ts} = Total Q of the driver

Q_{tc} = Total Q of the driver and box system

$$V_{box} = \frac{V_{as}}{\left(Q_{tc} / Q_{ts} \right)^2 - 1}$$

$$F_{-3dB} = \frac{Q_{tc} f_s}{Q_{ts}} \left[\frac{\frac{1}{Q_{tc}^{\ 2}} - 2 + \sqrt{\left(\frac{1}{Q_{tc}^{\ 2}} - 2 \right)^2 + 4}}{2} \right]^{1/2}$$

The spreadsheet calculates the size enclosure needed to yield a target Q of 0.577. Various low-end frequency responses are plotted for several values of quality factor in Fig. 2.

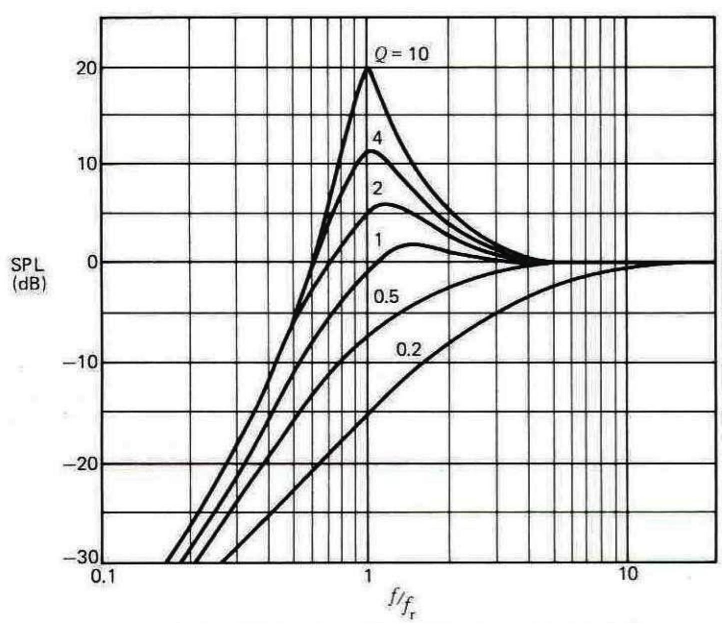


Fig. 2. Sound pressure response for various system quality factors.

Q=0.707 is a Butterworth alignment resulting in maximum flat frequency response. Q=0.577 is a Bessel response and yields maximum flat delay. Q=0.5 is critically damped and yields a transient perfect response. Q's less than 0.5 do not yield any know advantage while Q's greater than 0.707 are Chebychev (elliptical) filters resulting in a hump in the low-end frequency response and an increased roll-off slope [3]. High Q systems are commonly described as being 'boomy'. Placing a driver in a larger box will provide a lower system Q. Although a Q between .5 and .577 is desired, the size of the enclosure becomes excessively large.

While the Q of the driver/box alignment is very important many other factors are considered during the selection of drivers. A low order crossover is desired to yield good transients and smooth, gradual transitions form one driver to another. This means that the drivers must be selected so that they have a large passband, smooth roll-offs, and well-behaved responses outside of their passband. A well-behaved driver response will allow the use of a simple electrical network resulting in fewer electrical components in the signal path. The least efficient driver limits the system efficiency and the maximum linear excursion indicates the amount of power that can be accurately reproduced at low frequencies. The cost of each driver and its impedance response is also considered.

A one-inch diameter Morel MDT-33 tweeter was chosen because it meets the above requirements and exhibits superior power handling capabilities. A semi-viscous ferrofluid is contained in the voice coil gap providing extra damping and heat dissipation for power handling. The midrange driver is a 4.5-inch Morel MW-143 and the bass driver is a 10-inch Peerless 850146. Driver pictures and manufacture-published specs are displayed in Appendices 1-3.

1.3 Sub-Sections

After the drivers are chosen, a specific enclosure design is finalized for each driver. All six enclosures are constructed, and then measurements of electrical impedance and acoustic response are conducted. Measurement data is used to design and simulate various crossover responses including the filter and impedance correction circuits. After the design is finalized, a crossover is constructed from quality electrical components.

2. MECHANICAL ENCLOSURE

In a conventional loudspeaker all drivers are mounted on the same baffle. These drivers were placed in separate boxes to isolate vibrations and allow adjustment of the system group delay characteristics by moving one driver forward or backward with respect to the other drivers. If the baffle or any walls of the enclosure vibrate, they will act as unwanted acoustic sources adding distortion to the acoustic wave emitted from the driver’s diaphragm. The objective of the enclosure is to provide a stiff and damp structure on which to mount the drivers. A sealed box should completely damp the back wave while restricting the enclosure walls from vibrating. It is desirable to allow the forward wave to propagate from the driver unaltered by the effects of diffraction and interference. These undesirable affects can be caused by the edges of the cabinet and radiation from multiple sources. Because of wave diffraction, it is beneficial to have continuous large radius rounded edges along the edges of the baffle. All drivers are flush mounted, preventing diffraction effects caused by the edges of the driver frame.

An acoustic phenomenon known as the baffle step is an important consideration when choosing the baffle width. The baffle step causes a drop in the energy level of radiated waves by a factor of 4 (-6dB) as the frequency ranges from high to low. High frequencies are louder than the low frequencies and the transition point is a function of baffle width. The transition is centered about the frequency at which the acoustic wavelength equals half of the baffle width [4]. At higher frequencies (smaller wavelength) the width of the baffle is much greater than the length of one oscillation. The baffle can be approximated as an infinite wall, so the high frequencies are radiating into a “half space”. At low frequencies the long wavelength exceeds the dimensions of the baffle, thus the baffle no longer looks like an infinite wall. In fact, the baffle that is an infinite wall at high frequencies appears as a point source at low frequencies. The low frequencies are radiating into a “full space”. These low frequency waves must disperse to fill twice the volume that the high frequencies fill. Theoretically, the sound pressure level at a listening point is 6dB higher at high frequencies compared to low frequencies. One motivation for a multiple box design is the fact that different baffle widths can be chosen for different drivers. Each driver is mounted such that the baffle step transition occurs outside the operating range of the driver on that baffle.

2.1 Bass Enclosure Design

A sealed box is used for the bass driver because the enclosed air acts as a spring, helping the diaphragm's acceleration at the highest excursion points. When the cone is totally recessed, the pressure inside the cabinet has increased slightly. This pressure helps to quickly move the driver in the opposite direction. Sealed enclosures exhibit better transients (quick impulsive sounds) due to the spring action of the compressed/uncompressed air contained in an airtight cabinet. Anther popular design is a vented box, which acts as a Hemholtz resonator, extending low-end frequency response and efficiency at the expense of a smooth roll-off and better transient response.

The vibrating diaphragm of each driver generates a backward acoustic wave that is of equal power and completely out of phase with the forward wave. If these waves intersect, they will cancel each other creating a null in the frequency response. Because the backward wave is out of phase, it is desirable to completely damp the backward wave. The enclosure attempts to trap the wave in a sealed box and damp all vibrations so that the wave cannot propagate to the outside of the box. The interior material does a good job of coupling the acoustic wave into the wall of the enclosure and preventing it from reflecting back to the front of enclosure. If a reflected wave continues toward another absorbing medium, that is beneficial. The objective is to prevent the wave from escaping to the listening room where it will distort the accurate reproduction of the recording.

The bass cabinet walls are constructed of high quality 1.25-inch medium density fiberboard (MDF). MDF was chosen as the premier material for its inexpensive cost, heavy mass, decent stiffness, and good damping characteristics. MDF is a composite wood material processed from very small shreds of natural wood. The process includes a significant amount of glue, which leads to the superior damping properties of MDF with respect to solid natural wood. All joints are 90° lock joints, providing maximum glue area and strength.

The inside of the box includes a shelf brace to improve stiffness and reduce vibration. The brace is located off-center so that additional resonances are not created. The brace is positioned in the direction of the two longest axes in order to raise the fundamental resonance frequency as high as possible. The objective is to raise the fundamental resonance frequency above the operating range of the bass driver. Iverson [5] has researched the placement of shelf braces and the resulting fundamental frequency of resonance. The bass cabinet walls are also stiffened by rigidly attaching steel supports along the interior of the cabinet walls. The interior of the cabinet is covered with oil-based modeling clay. The oil-based clay never dries out, easily sticks to the interior of the cabinet, adds mass to the enclosure, provides damping and can be applied in varying thickness to different regions of the walls.

The baffle of the bass box is constructed differently because the drivers are mounted on this surface. A 1.75-inch of MDF panel is used for extra strength. Two steel stiffening supports are added to the interior of the baffle.

2.2 Bass Enclosure Construction

The boxes are constructed in a professional cabinetry shop. Appendix 4 includes several pictures of the bass cabinet interior. All machining is done with exceptional precision. The enclosure walls and joints are cut with a table saw. A pattern for the driver hole is cut using a wing cutter attachment on a drill press. After the pattern is fabricated, a router is used to cut the driver hole into the baffle. A thick baffle is necessary for stiffness, but the driver will be acoustically loaded in an undesirable way if the woofer is placed in this 2 inch long "tunnel". Considering this undesirable affect, a router is used to remove a portion of thick wood around the rear of the driver hole.

A drill press is used to machine holes for screws that attach the driver to the cabinet. The shelf brace is tightly inserted into datto slots machined into the walls of the cabinet. An asymmetric pattern of holes is cut into the brace using a jigsaw to allow free movement of air within the enclosure. Steel stiffening supports are attached with epoxy to provide an extremely rigid connection. Holes for the binding posts are machined as small as possible to maintain an airtight enclosure. Weather stripping is placed around the mounting frame of the driver to ensure that no air leak exists.

The panels are finished with birdseye maple veneer and the corners contain trim pieces of solid birdseye maple. The aesthetic appearance of the cabinet is quite extraordinary because a black driver is mounted in a cabinet made of a very light colored wood. The loudspeaker appears to be wearing a 'tuxedo in reverse.' An image of the loudspeaker is included as Fig. 3.

Fig. 3. Audio loudspeaker drivers mounted in enclosures.

2.3 Midrange and Tweeter Enclosure Design

Figure 4 shows the measured baffle step response for twelve baffle shapes.

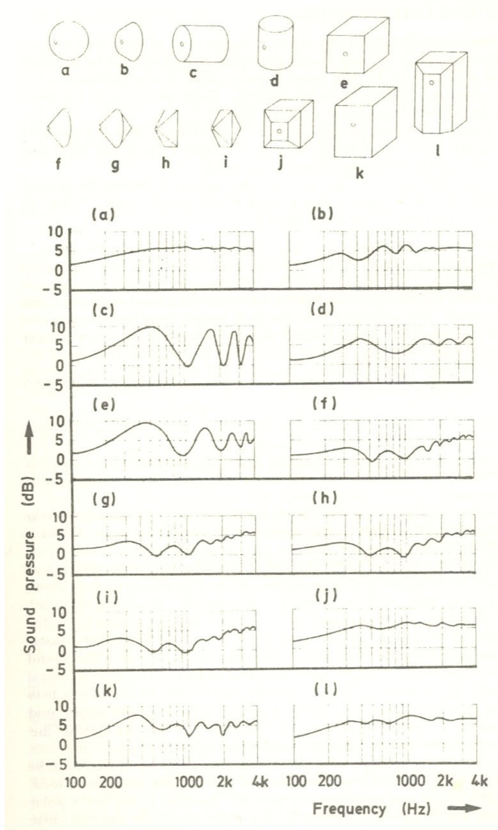


Fig. 4. Measured baffle step responses for 12 different baffle shapes.

It is clear that the best and smoothest response results form a spherical enclosure. The midrange and tweeter boxes are similarly designed with large radius roundovers to emulate this spherical shape. The midrange and high frequency boxes contain a driver mounted in an egg/oval shaped enclosure. The box interior is designed so that it is very asymmetrical, minimizing box resonances. This box will have no parallel walls. Parallel walls allow a standing wave to continuously bounce back and forth creating box resonance peaks in the frequency response.

An important consideration is the fact that two drivers should be placed no farther apart than the distance of one full wavelength at the crossover frequency. Both drivers are producing equal amounts of power at the crossover frequency; therefore, interference effects become excessive if the drivers are located too far apart. This is sometimes referred to as a comb filtering affect. This can become challenging, as the wavelength at a crossover frequency of 2500Hz is a mere 5.4 inches. Thus, 5.4 inches should be the maximum center-to-center distance between the tweeter and midrange if a 2500Hz crossover frequency is chosen. Realistically this cannot always be achieved, but lowering the crossover frequency or moving the drivers closer together can alleviate the problem. For this reason, the drivers are moved closer together by displacing the midrange upward and displacing the tweeter downward. Diffraction effects are also improved by displacing the driver off-center. This creates a continuously varying distance from the center of the driver to the edge of the baffle. The resulting diffraction effects are smeared across a range of frequencies rather than causing a sharp peak or dip at one frequency. The midrange box also contains a structural shelf brace and clay interior. Fig. 5 is an image of the midrange enclosure.

Fig. 5. Midrange enclosure.

2.4 Midrange and Tweeter Enclosure Construction

Because veneer cannot be used on a curved surface, the midrange and tweeter cabinets are constructed from solid birdseye maple. Although this solid wood lacks good damping properties it is extremely stiff. The egg-shaped boxes are constructed in a very labor-intensive process. Starting with 6 two-inch thick square pieces of solid hardwood, circular holes of varying size are cut in the center of each piece of wood. One of the pieces is selected as the baffle and a driver hole is carefully machined. Next, two adjacent squares are placed in a vice and hand tools are used to make the step of two different size circles a continuous interface. Each piece is properly tooled so that the interior of the enclosure is an asymmetrical oval shape. The pieces of wood can then be glued together to form a box that is egg shaped on the inside but still rectangular on the outside. After this is accomplished, the box is turned on a wood lathe to work the outside surface into an egg form. Bracing supports are easily implemented by cutting two half circles instead of a full circle. The support is left as a strip of wood running across the interior of the box. This method of bracing is far superior to constructing a support and fastening it to the box. The support and the box exterior are actually one piece of continuous wood providing significant strength. The drivers are mounted in routed holes to provide flush mounting with the baffle, reducing diffraction effects. All cabinets are finished with a clear lacquer to protect the wood while preserving its natural light color.

3. TEST AND MEASUREMENT

Testing and measurement is an important part of this project for two reasons. The first involves verifying that the system meets the design requirement such as low Q and an airtight sealed cabinet. Measurements can also be used for simulating crossover designs during the electrical design process.

3.1 Enclosure Air Leak Test

Air leaks in sealed cabinets can be detected by driving the speaker with a 5 or 10Hz signal and traversing the area in question with a flame from a cigarette lighter. If a flaw exists, air will be forced through the crack causing the flame to flicker. Movement of air is not detected around the frame of the drivers, indicating that an adequate seal has been attained.

Solid wood construction, as used in the tweeter and midrange, is not recommended by any experienced woodworkers. Using solid wood in this manner led to severe problems because large movement occurs as the moisture content of the wood changes. Even though the wood was thoroughly dried before construction, significant moisture change occurs as the seasons change. An incomplete glue joint allowed movement in the wood to cause a large crack in the midrange cabinet. The crack can be seen in Fig. 6.

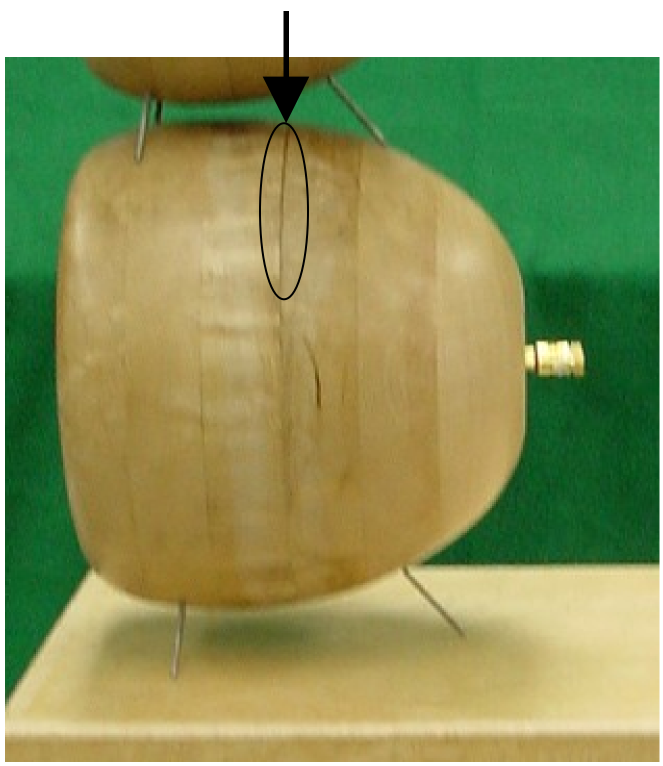


Fig. 6. Crack in the midrange enclosure.

Using the air leak test it was verified that the large crack did allow a significant leak at 5Hz. A leak could not be detected at 100Hz. This indicates that the box should behave satisfactorily across its usable frequency range (250Hz- 5kHz).

3.2 Electrical Impedance Measurement

National Instruments LabView was used in conjunction with an HP4192A Low Frequency Impedance Analyzer to record impedance magnitude and phase at 2000 frequencies between 10Hz and 20kHz.

Impedance measurements for all 6 drivers mounted in their enclosures are displayed in Appendix 5. The tweeters exhibit a very strange impedance response that does not conform to the work of Theil and Small. This is evident because the impedance magnitude is not symmetric about the resonance frequency. It is believed that the unorthodox impedance is due to the presence of ferrofluid in the voice coil. Ferro fluid does an excellent job of damping the impedance peak, Zmax=10 Ohms. Unfortunately the resonance occurs at a significantly higher frequency than the manufacture specifications. Manufacture specifications claim that resonance occurs at 700 Hz ±10%, but the measured resonance frequencies are 1250 and 1400Hz.

3.3 Acoustic Response Measurement

LabView was also used to automate the acoustic response measurement. A block diagram of the impedance and acoustic measurement setup is included as Fig 7.

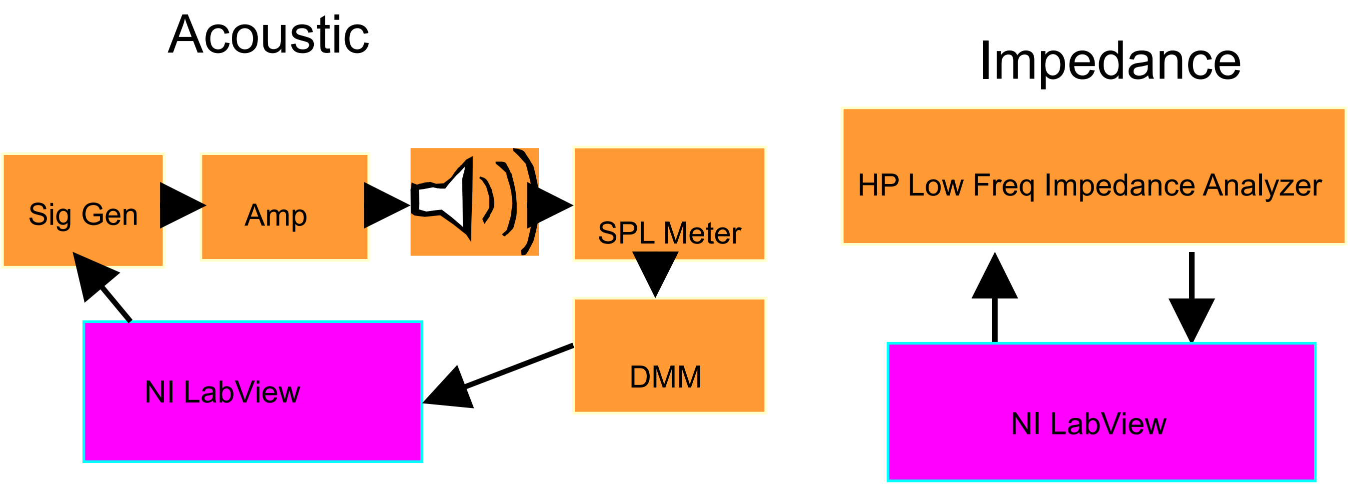


Fig. 7. Block diagram of acoustic and impedance test setup.

A signal generator's output is amplified and routed to the driver. An SPL meter is used to detect the acoustic magnitude at a distance of one meter from the baffle. A Fluke HYDRA is used to measure the peak-to-peak voltage of the SPL meter's AC output. The LabView program increments the signal generator through 2000 frequencies and records the SPL meter's output at each frequency. Because the SPL meter's output is constantly varying, 10 voltage measurements are recorded, the highest and lowest values are discarded and the remaining 8 are averaged. All six acoustic response measurements are displayed in Appendix 6. Note the similarity between the left and right channels. This is necessary to achieve good imaging. Imaging is the ability to hear the spatial positioning of an individual musician or instrument. Throughout the entire project, much attention was donated to ensuring that the left and right channels are as identical as possible. As expected from manufacture specifications, the tweeter is about 3 dB more sensitive than the midrange or woofer.

3.4 Quality Factor Measurement and Calculation

The measured impedance response and T/S equations [6];

$$r_0 = \frac{R_{\max}}{R_e}$$

$$Q_{ms} = f_s \frac{\sqrt{r_o}}{f_2 - f_1}$$

$$Q_{es} = \frac{Q_{ms}}{r_o - 1}$$

$$Q_{ts} = \frac{Q_{ms}\, Q_{ms}}{Q_{ms} + Q_{es}}$$

are used to calculate the Q of the driver/box alignment for the midrange and woofer. f_1 and f_2 are the frequencies at which the system impedance is equal to r_o. T/S theory is valid if the impedance curve is symmetric about the resonance frequency on a log frequency plot ($f_1 f_2 = f_s^{\,2}$). Measured Q's for the midranges are 0.63 and 0.69. Measured Q's for the woofers are 0.63 and 0.65. A Q cannot be measured for the tweeter because the impedance response does not conform to T/S theory.

4. ELECTRICAL CROSSOVER

A three-way crossover is located outside the driver enclosures so that electrical components can be altered after the boxes have been completed. The crossover is passive, meaning that it consists of passive elements including resistors, capacitors, and inductors connected between the amplifier and the driver. An active crossover utilizes active (solid state) electrical components such as op-amps at low voltage level (prior to amplification). Distortion levels are lower when a low level, active crossover is used. When using an active crossover, one amplifier is needed for each driver because the signal is filtered before amplification. An external crossover has the advantage that it allows the flexibility to alter a particular crossover or switch among entirely different crossovers, including passive, active, and digital.

A three-way crossover consists of three filters, a high pass for the tweeter, a band pass for the midrange, and a low pass for the bass driver. Series, parallel and cascaded crossover topologies were considered (Fig. 8).

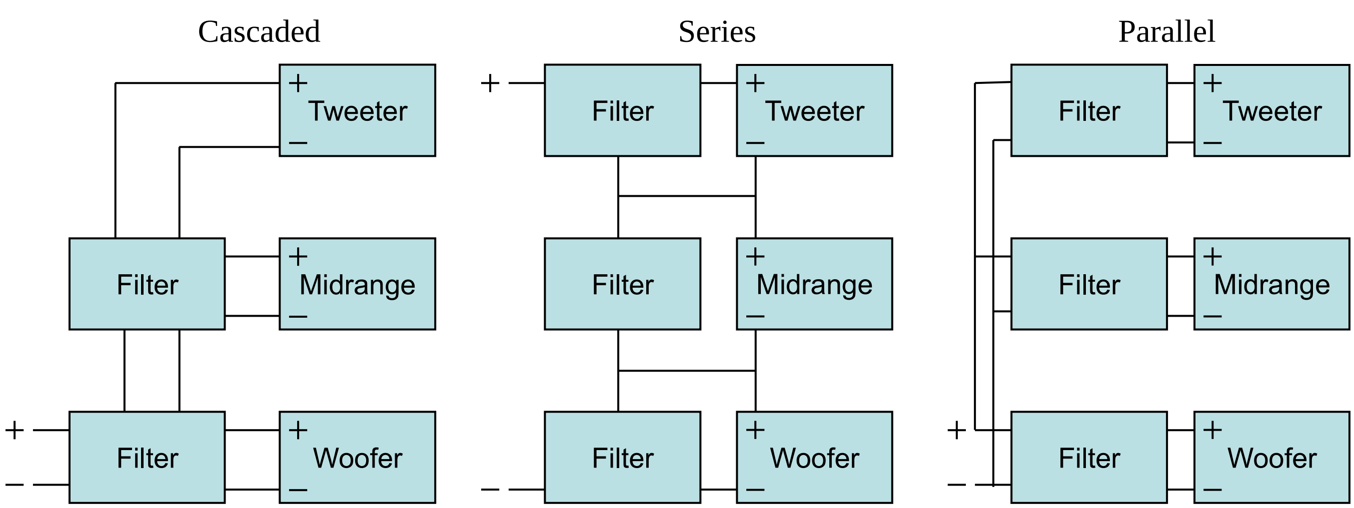


Fig. 8. Block diagrams of cascaded, series, and parallel crossovers.

The most significant decisions include the order of the crossover slope and the crossover frequencies. Higher order crossovers have steeper slope on an output vs. frequency plot; they squash output outside of the pass band. Each order of a filter is equal to -6dB per octave slope, so a first order falls at a rate of -6dB per octave and a second order falls at -12dB per octave. Likewise third and fourth order filters are also common. Higher order filters allow a driver to have terrible frequency responses outside of their usable frequency range. The drawback of high order filters is distortion of the phase response and a transition from one driver to another that is quite abrupt. This phase inaccuracy creates one type of distortion that will be minimized.

The order of the crossover is the same as the number of reactive elements (capacitors and inductors) in the filter portion of the circuit. A textbook fist order filter is not adequate as it consists of simply one inductor or capacitor. A realistic first order filter will have gradual frequency roll-off but can be quite complex. In order for a filter to behave satisfactorily, each branch of the filter must be terminated with the same resistive impedance. To achieve this, impedance correction circuits are designed and added in parallel with the drivers.

All drivers have undesired frequency response and/or impedance characteristics at the resonance frequency. Crossover frequencies must be at least one octave from the resonance frequency. When using first order crossovers it is necessary to have two octaves between the edge of the passband and the resonance frequency of the driver. The human voice ranges from 120Hz to 3kHz. The critical frequency range of musical content is considered to be 300Hz to 3kHz. The intention is to choose two crossover frequencies such that this region (300Hz - 3kHz) is placed vastly on the midrange driver.

One goal is maintaining a well-behaved (linear) phase response. In the loudspeaker world this is called time alignment, making sure that each frequency arrives to the listener at the appropriate time with respect to the waves of other frequencies. This, along with first order crossovers and low Q, is a requirement for a speaker that has excellent transient behavior. Good transient behavior means that an impulsive input signal will result in an output acoustic wave that is impulsive and does not “ring”.

4.1 Crossover Design

HP ADS 2002 is used to simulate many crossover designs. The simulated circuits are terminated with measured impedance values. This results in very accurate simulations. Each simulation produces plots of voltage magnitude and phase versus frequency for each driver as well as the total summed response. This output is considered in conjunction with the measured acoustic response of each driver to determine if the circuit is well suited to the design goals and the drivers being used.

There are two types of impedance correction circuits, series notch filters and zobels. A series notch filter includes a series combination of an inductor, capacitor, and resistor placed in parallel with the driver. At the frequency where the inductor and the capacitor resonate, the filter sees the driver in parallel with the resistor, thus lowering the impedance near the driver’s resonance. A zobel consists of a capacitor-resistor series placed in parallel with the driver. This circuit compensates for a driver’s voice coil inductance that causes a raise in impedance with increasing frequency [7]. With the addition of this circuit, the filter will see the driver in parallel with a resistor at high frequencies. The parallel combination reduces the impedance seen by the crossover at high frequencies. The tweeter has a very moderate impedance response that does not necessitate the use of impedance correction. A series notch filter can be used to completely eliminate the 10-ohm impedance peak at resonance. Both a series notch filter and a zobel are recommended for the midrange. A zobel is absolutely necessary for the woofer because its impedance rises to 85 ohms at 20kHz. Although the 50-ohm impedance peak at the woofer’s resonance is quite high, it is not necessary to use a series notch filter. Behavior of the system impedance at 38Hz is not extremely important. The woofer is the only driver producing power at this frequency and its acoustic response is well behaved. Building a series notch circuit for the woofer would require an extremely large inductor. These impedance compensation circuits are necessary for the filters to produce smooth roll-offs at the designed frequencies. Appendix 7 displays final designs of the impedance correction circuits along with the simulated input impedance.

Crossover points of 450Hz and 2500Hz were chosen because these locations maximize the length of flat driver acoustic response on each side of the crossover frequency. For example, the 450Hz location is chosen because the woofer exhibits flat frequency response for approximately 1 octave above 450Hz and the midrange exhibits flat frequency response for approximately 1 octave below 450Hz.

Any filter of order larger than one cannot theoretically reproduce a square wave correctly. In order to reproduce a square wave, a filter must be minimum phase. Minimum phase filters include 1st order Butterworth, series filters, and a few other complicated, mathematically derived filters, which often times cannot be constructed [8]. Theoretical reproduction of a square wave indicates that the crossover should be able to deliver good transient characteristics.

Because these drivers have quite limited usable frequency range and the tweeter's 1250 Hz resonance frequency, it appears that a 1st order crossover might not function acceptably in this system. Considering the current technology of acoustic drivers, a 4-driver system may be necessary in order to use 1st order filters. Even order Butterworth filters do not yield a flat summed frequency response, thus they are not recommended. A third order cascaded Butterworth filter produces adequate attenuation in the stopband and a flat summed response.

4.2 Crossover Construction

Four filters were constructed including 450Hz 1st and 3rd order Butterworth and 2500Hz 1st and 3rd order Butterworth. Several switches allow 'on the fly' switching between 1st-1st, 1st-3rd, 3rd-1st, and 3rd-3rd order crossovers. A tweeter series notch, midrange zobel and series notch, and woofer zobel were constructed. Switches allow the user to switch each impedance correction circuit in or out of the crossover. This provides the ability to closely compare and subjectively evaluate the results that are quantitatively represented in the simulations. Circuit schematics for 1st and 3rd order crossovers and a simulated response for the 1st order crossover are included in Appendix 8.

The crossover circuit is constructed on a ¾-inch piece of plywood. Copper contact pads are cemented into a ½ inch deep hole. This results in a strong connection that will not conduct electricity into the crossover substrate. The inductors are anchored to the plywood with silicone sealant while solder joints secure the resistors and capacitors.

4.3 Crossover Component Testing

The ideal inductor has zero DC resistance and an inductance that does not vary with frequency. Air core inductors wound with large gauge wire will yield a nearly linear response and low DC resistance. Iron core inductors reduce the number turns required for a given inductance but result in an inductance that varies as a function of frequency. It is important to use reasonably linear inductors because the simulation assumes that the inductors are perfect (i.e. DCR=0 and $L(\omega)$=constant). In order to achieve a low DC resistance the inductors are wound with large 16-gauge wire. The inductance is measured so that inductance values are exactly the value indicated in the simulation. Three different inductors were constructed and tested to determine their quality. Fig. 9 is a measured plot of inductance verses frequency for a sloppily wound inductor on a plastic core, a tight wound inductor on a wood core, and a loose wound inductor on a metal core.

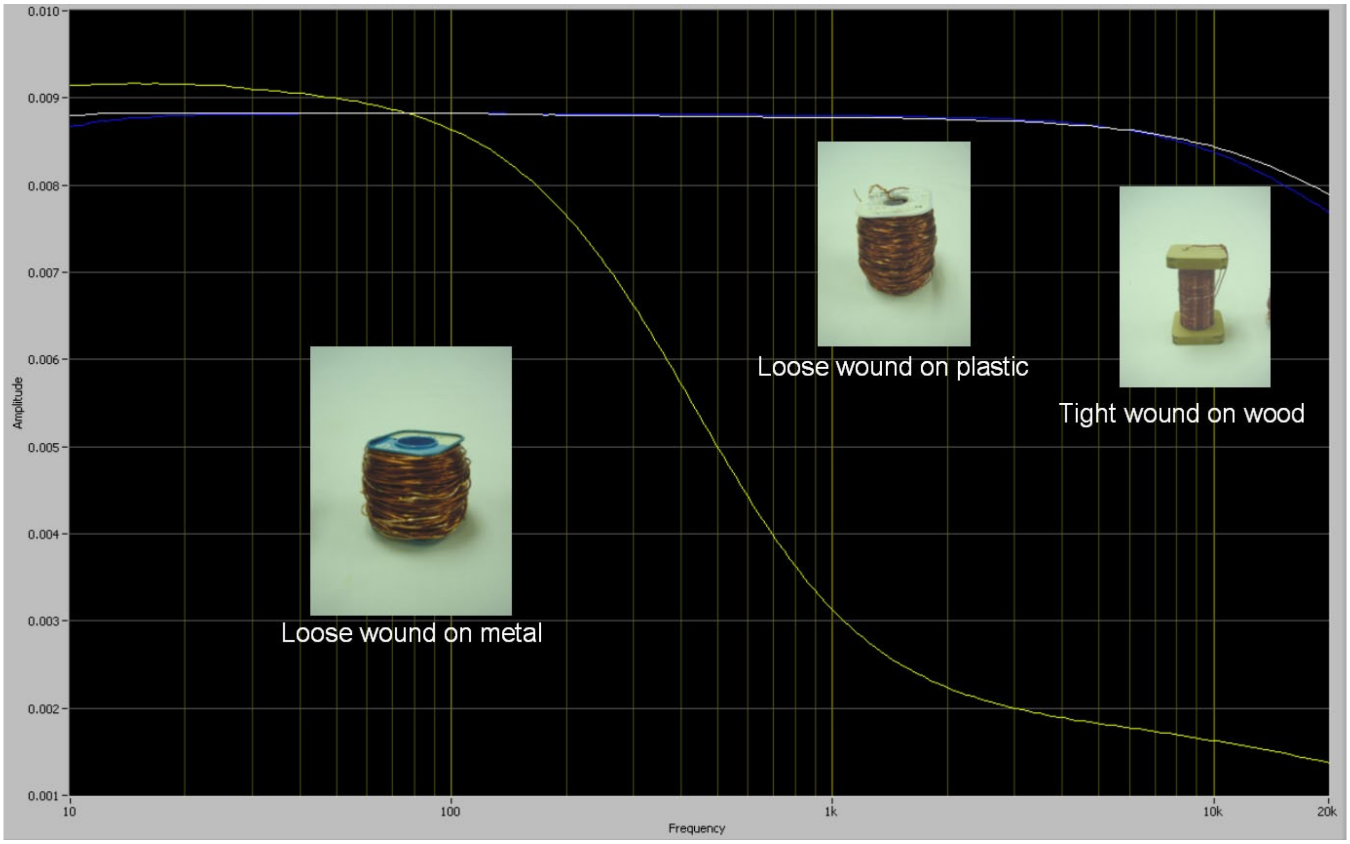


Fig. 9. Inductance vs. frequency for 3 inductors

The metal core is quite unacceptable because its inductance drops by a factor of 8 from 10Hz-20kHz. Loose, sloppy winding verses tight winding does not make an appreciable difference in the audio frequency range and wood is an acceptable core material.

5. COST

The costs are difficult to asses accurately because a large amount of time was required to build the prototype and develop software for the measurement process. Only the cost of the parts has been included. Likewise, the cost of software development is not included because this is only executed once, and then the measurement software can be used indefinitely to assist in any subsequent loudspeaker design.

If the design were to be offered as a commercial product many aspects would be changed. The wood construction by hand would be eliminated and replaced by purchasing enclosures or fabricating them by some industrial means. The labor required to shape wood by hand is far too costly to provide a product that can be successfully marketed.

Table 1 lists the unit price, quantity, and total cost of all physical parts included in the loudspeaker. The costs of design and simulation software, programming languages, and test equipment are not included.

Table 1 – Cost of loudspeaker parts.

Item	Unit cost ($)	Quantity	Cost ($)
Morel MDT-33	105	2	210
Morel MW-143	110	2	220
Peerless 850146	65	2	130
Speaker Wire	4.25	10	42.5
Binding Posts	4.25	14	59.5
Solid Birdseye Maple	300	1	300
Birdseye Maple Veneer	100	1	100
MDF	40	2	80
Plywood	45	1	45
Copper Wire	0.0625	2000	125
Resistors	3	12	36
Capacitors	5	26	130
Switches	2	24	48
Clay	80	1	80
Total Parts Cost			1606

6. CONCLUSIONS

A complete audio system has been designed and constructed which closely approximates the original design goals. The target Q of 0.577 was not attained because limited resources reduced the enclosure size. The Q's remain lower than the Butterworth response (0.707) and the left and right channel exhibit almost identical impedance and acoustic responses. The crossover is not currently functioning due to improper wiring of the switches. Once the crossover is working, various circuits will be able to be demonstrated from which a final design can be chosen. The impedance correction circuits appear to function quite well as demonstrated by the simulation. Because a flat microphone is not available, the SPL meter is used. This provides acoustic response magnitude but not phase information that would also be attained with a flat microphone.

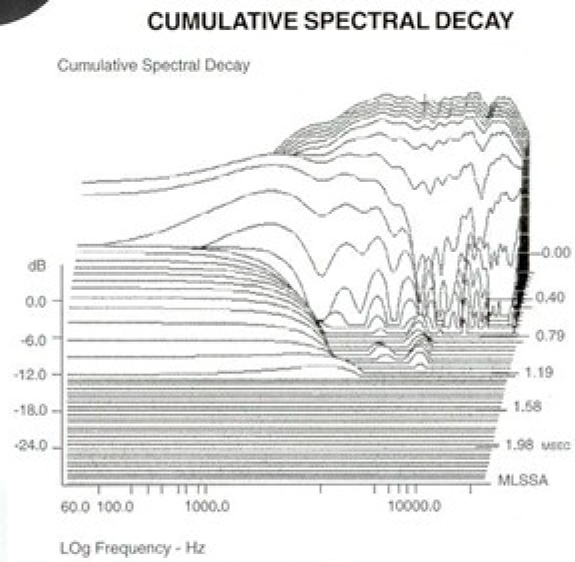
Many difficulties were present during construction of the enclosures. At one time two of the bass cabinet walls were dropped on a concrete floor, totally destroying three corners that had already been fully machined. At this point and several other times, professional woodworking advice was requested. A biscuit jointer was used to securely attach a new block of wood that was then machined to the previous shape. Turning the solid maple boxes into an egg shape proved to be a very slow process that requires very sharp tools and a lot of patients. There were also many areas of the veneer that were damaged and then patched or repaired.

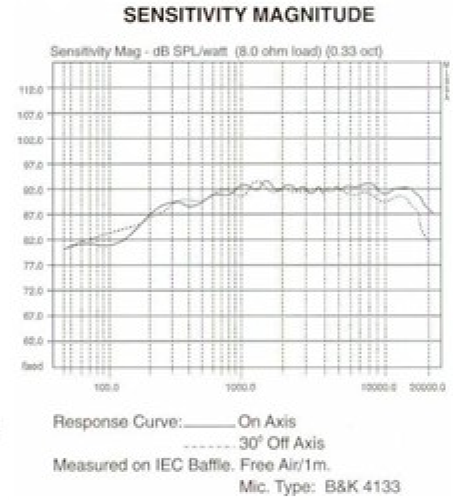
Difficulties in the test and measurement process involve communication with the test equipment. Because an HP GPIB card is used, the National Instruments drivers could not automatically execute the desired commands. The drivers acquired from NI were altered before communication with the instrument could be established. Another problem arose while taking data for a long period of time. The LabView driver caused the computer to crash due to excessive use of memory. Removing the error handler portion of the program alleviates this problem. Also the text file is only opened and closed once rather than opening and closing every time the file is written.

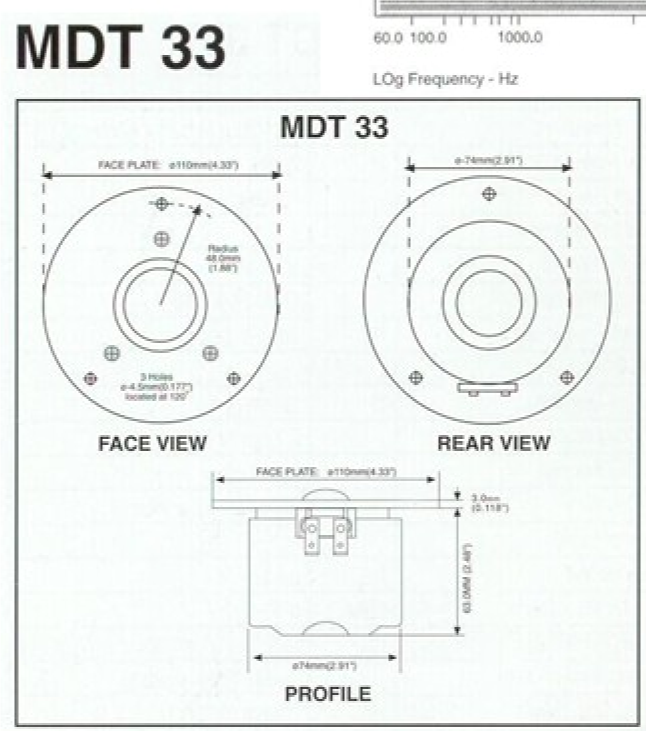
There are many avenues of further work being considered for this project. The first and most important is to export data from the HP ADS simulations and multiply the filter's output response by the acoustic response of each driver. This will yield an extremely accurate representation of the driver's acoustic output and is absolutely necessary for accurate simulation and design. A more thorough investigation of series and other minimum phase crossovers is desired. There is a big interest in designing and constructing a digital and/or active crossover for this system. A significant amount of additional research can be conducted to determine the quality of crossover components. It would be beneficial to measure the impedance verses frequency for all resistors, inductors, and capacitors. Future investigation could include fastening a micro-electro-mechanical sensor to the cone of the woofer and midrange for recording the displacement, velocity, and acceleration of the diaphragm. This sensor can also be used as feedback for controlling the behavior of the diaphragm. An entirely different area of investigation could be calculation of acoustic reflection coefficients for various materials and wall thickness.

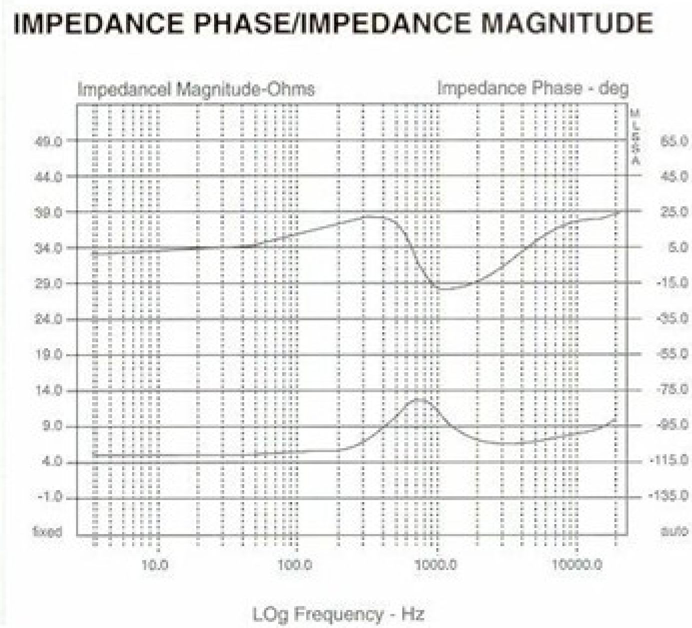
APPENDIX 1. TWEETER DATA

All manufacture published specifications for the Morel MDT-33 tweeter.



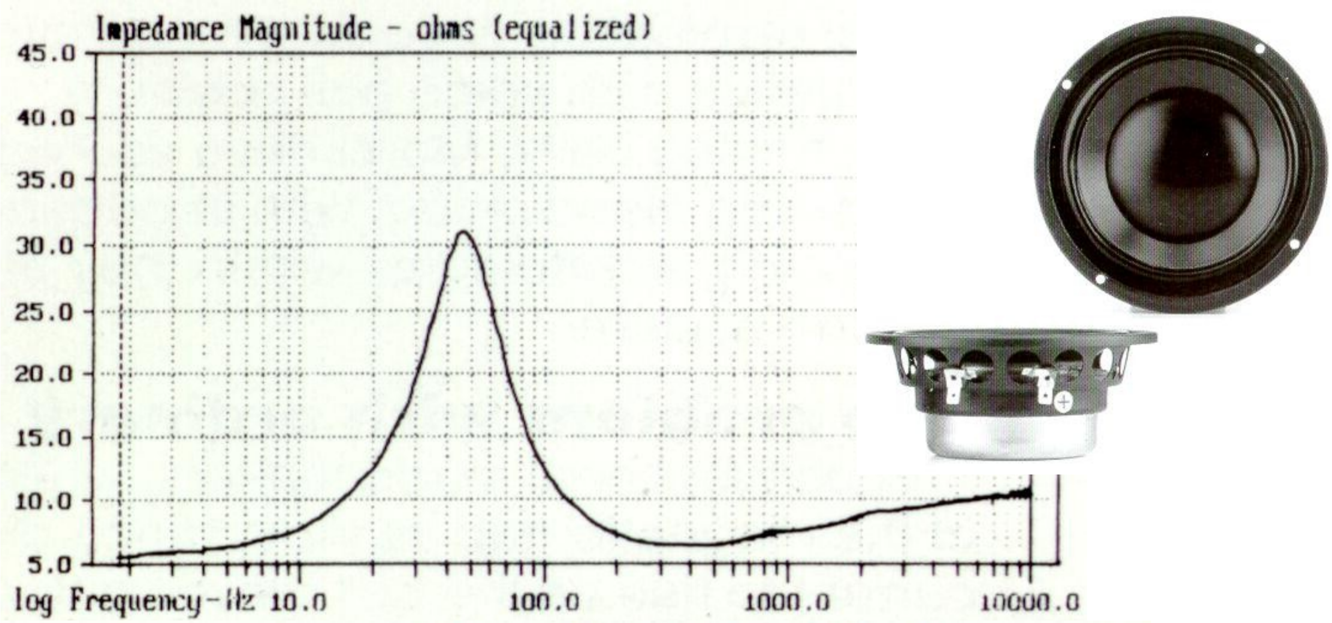


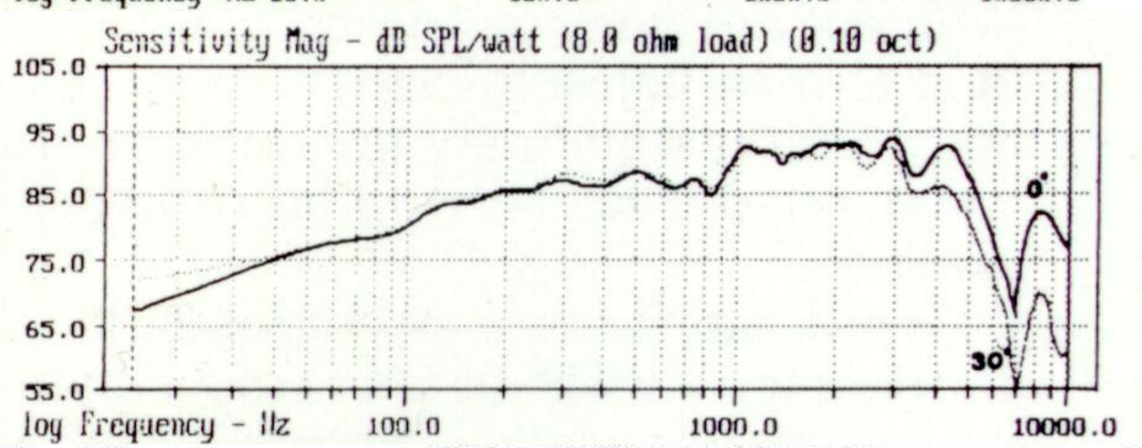




APPENDIX 2. MIDRANGE DATA

All manufacture published specifications for the Morel MW-143 midrange.





Overall Dimensions	Ø-142mm (5.5") x 52mm (2.0")	Voice Coil Height	12mm (0.47")
Nominal Power Handling (DIN)	150 W	X – Max. Linear Excursion	2 x 3.5mm (2 x 0.137")
Transient Power – 10ms	1000 W	B – Flux Density	0.86 T
Voice Coil Diameter	75mm (3")	BL Product (BXL)	7.20 NA
Voice Coil Type / Former	Hexatech Aluminium	Qms – Mechanical Q Factor	1.48
Frequency Response	45-4800 Hz	Qes – Electrical Q Factor	0.31
FS – Resonant Frequency	47 Hz	Q/T – Total Q Factor	0.26
Sensitivity 1W/1M	89 dB	Vas – Equivalent Cas Air Load	14 litres (0.5ft³)
Z – Nominal Impedance	8 ohms	MMS – Moving Mass	9.4 gm
RE – DC Resistance	5.3 ohms	Cms	1226µM / Newton
LBM – Voice Coil Inductance @ 1 Khz	0.11 mh	SD – Effective Cone / Dome Area	90 cm²
Magnetic Gap Width	1.35mm (0.053")	Cone / Dome Material	DPC (Damped Polymer Composite)
HE – Magnetic Gap Height	5mm (0.196")	Nett Weight	0.95 kg

APPENDIX 3. WOOFER DATA

All manufacture published specifications for the Peerless 850146 woofer.

CSX 257 H

Thiele Small parameters:

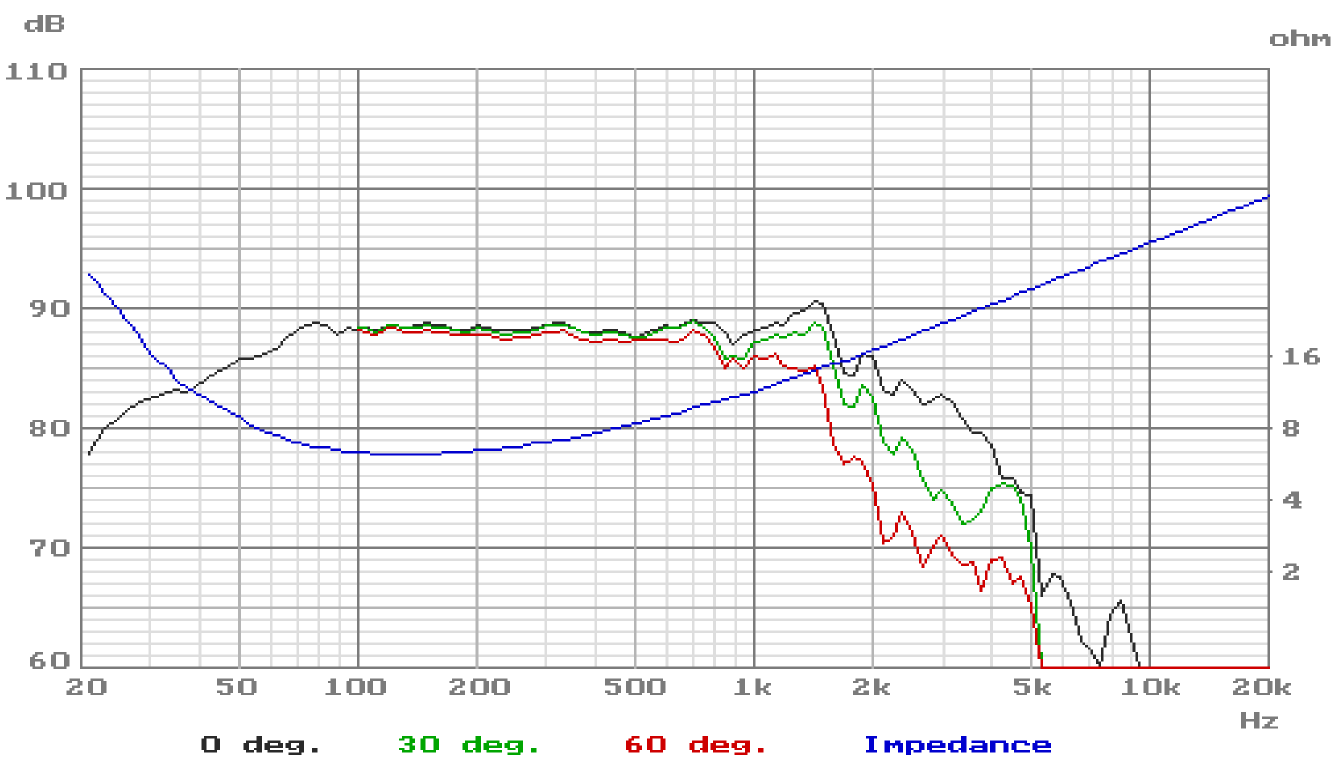
			Free air	Common	Baffled
Nominal impedance	Zn	(ohm)		8	
Minimum impedance/at freq.	Zmin	(ohm/Hz)		6.2/130	
Maximum impedance	Zo	(ohm)		40.3	
DC resistance	Re	(ohm)		5.5	
Voice coil inductance	Le	(mH)		2.9	
Capacitor in series with 8 ohm (for impedance compensation)	Cc	(µF)		25	
Resonance Frequency	fs	(Hz)	22.6		21.9
Mechanical Q factor	Qms		2.56		2.64
Electrical Q factor	Qes		0.40		0.42
Total Q factor	Qts		0.35		0.36
F (Ratio fs/Qts)	F	(Hz)			61
Mechanical resistance	Rms	(Kg/s)		2.87	
Moving mass	Mms	(g)	51.9		55.1
Suspension compliance	Cms	(mm/N)		0.96	
Effective cone diameter	D	(cm)		20.5	
Effective piston area	Sd	(cm²)		330	
Equivalent volume	VAS	(ltrs)		144.4	
Force factor	Bl	(N/A)		10.0	
Reference voltage sensitivity Re 2.83V 1m at 130 Hz (Measured)		(dB)			88.2

Magnet and voice coil parameters:

Voice coil diameter	d	(mm)	39
Voice coil length	h	(mm)	26
Voice coil layers	n		4
Flux density in gap	B	(T)	0.85
Total useful flux		(mWb)	1.34
Height of the gap	hg	(mm)	8
Diameter of magnet	dm	(mm)	115
Height of magnet	hm	(mm)	22
Weight of magnet		(kg)	0.87

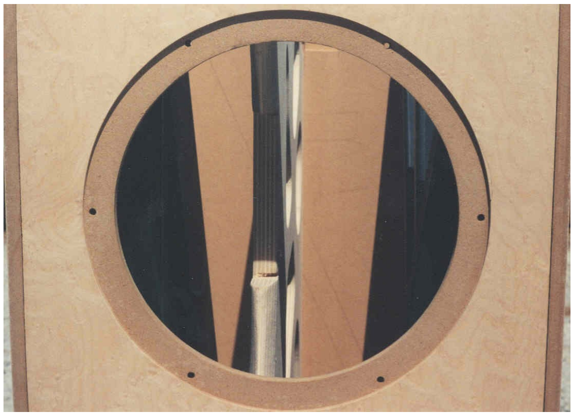
Power handling:

Long term Max System Power (IEC)	(W)	200



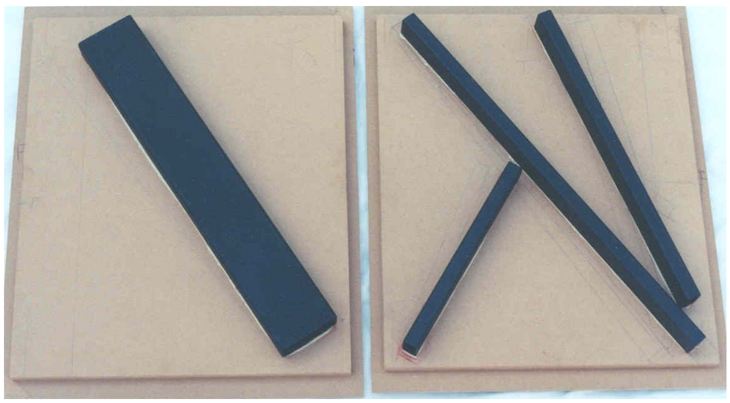
APPENDIX 4. BASS ENCLOSURE INTERIOR

Interior images of the bass enclosure are presented below.



Driver port view

Overhead view



Sidewalls w/ epoxied steel reinforcement

Back & Baffle

Brace w/ Clay

APPENDIX 5. IMPEDANCE MEASUREMENT DATA

Plots of impedance verses frequency for all six drivers are presented below.

Tweeter Mag

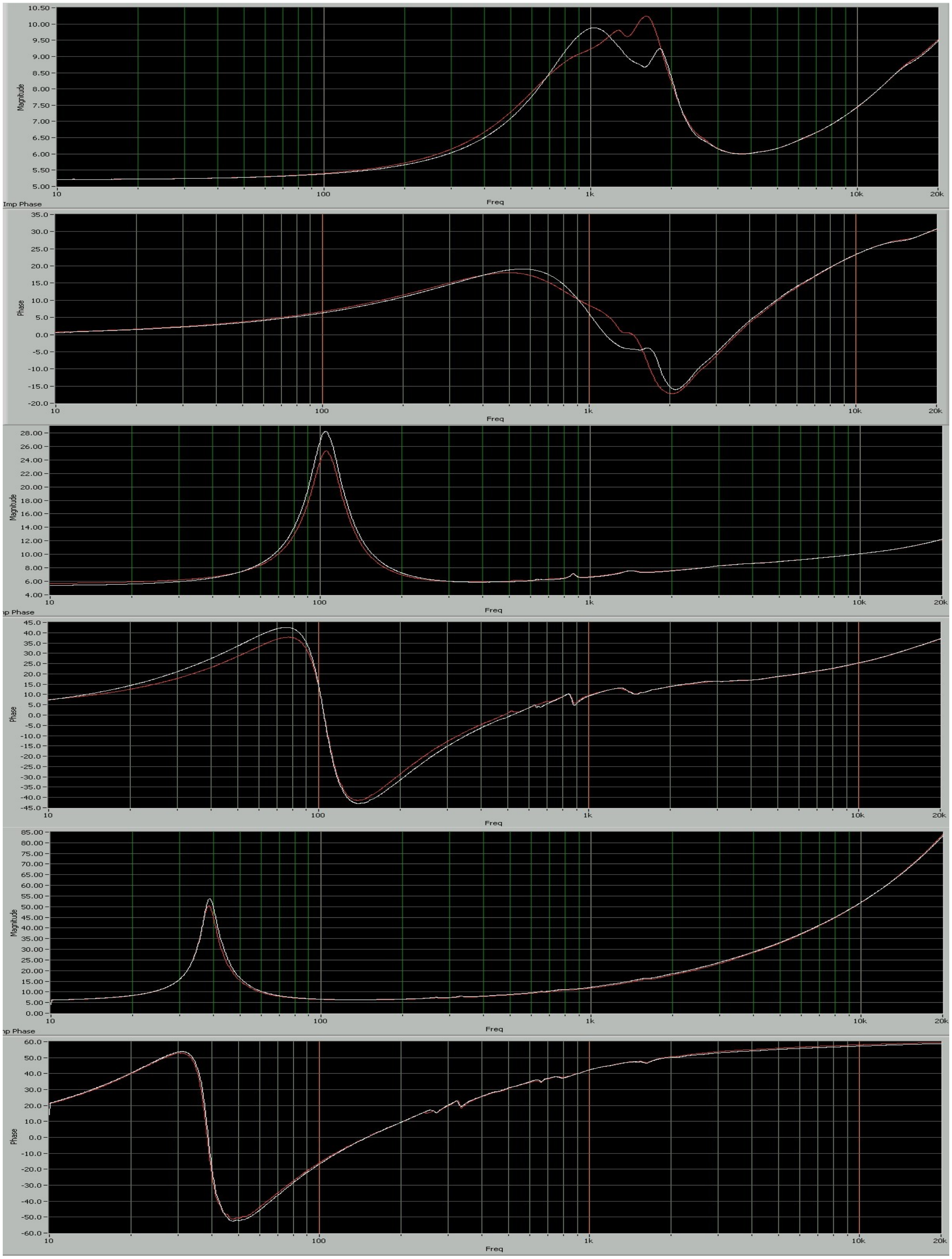
Tweeter Phase

Midrange Mag

Midrange Phase

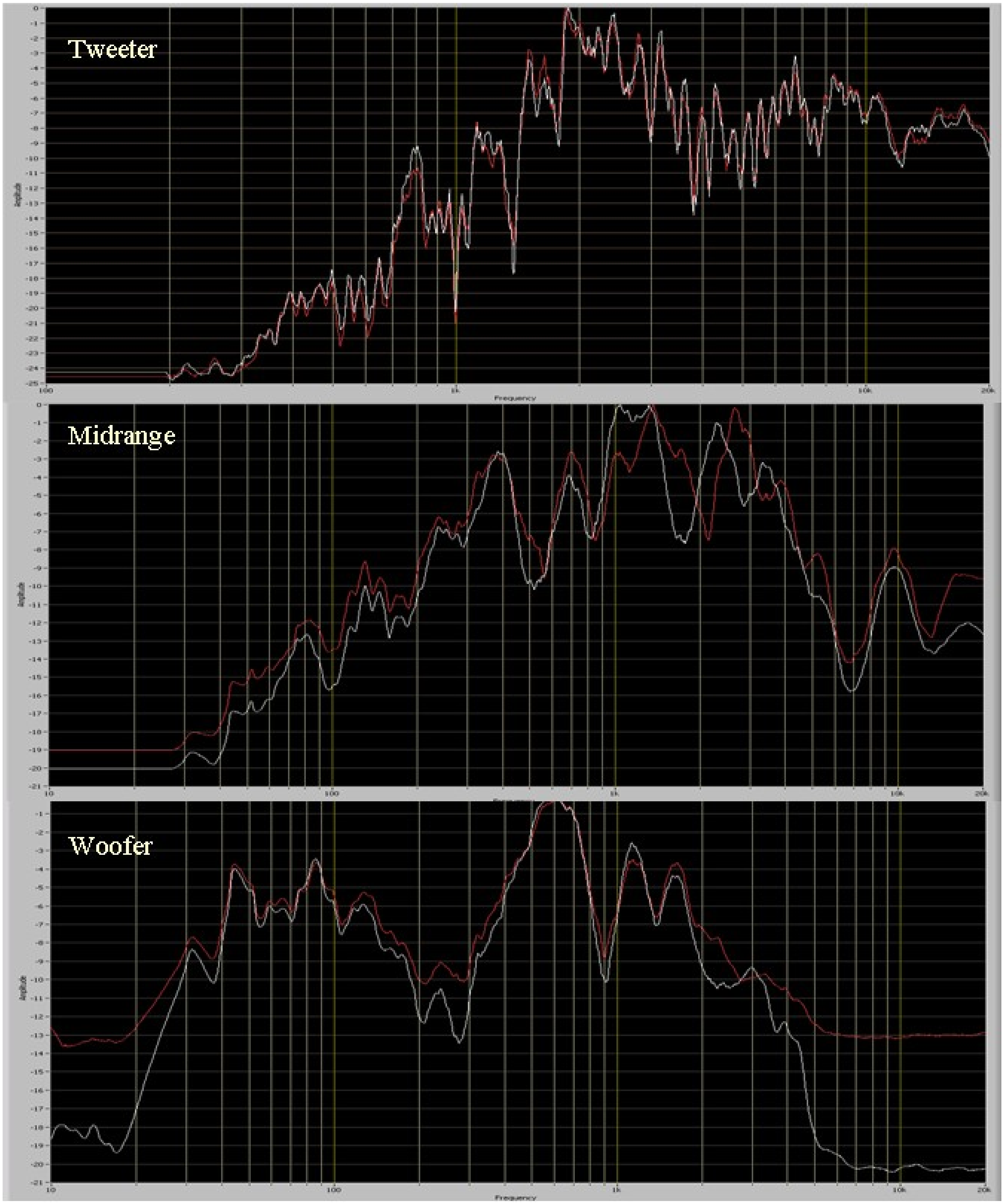
Woofer Mag

Woofer Phase



APPENDIX 6. ACOUSTIC RESPONSE MEASUREMENT DATA

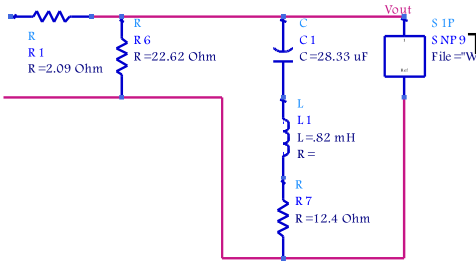
Below are graphs of the measured acoustic response magnitude for all six drivers.



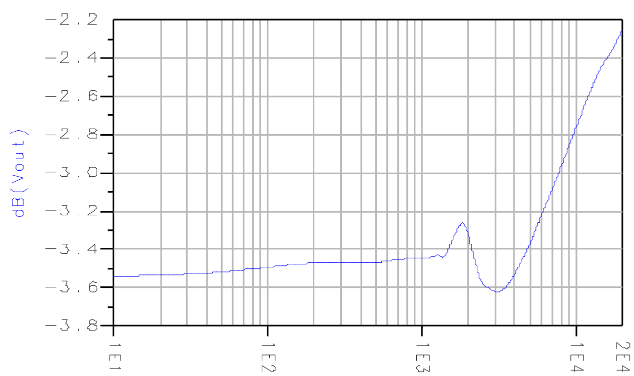
APPENDIX 7. IMPEDANCE COMPENSATION CIRCUITS

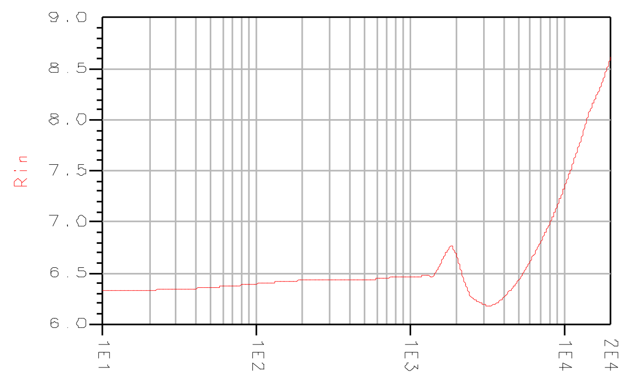
Circuit schematics and input impedance simulations are presented below.

Tweeter



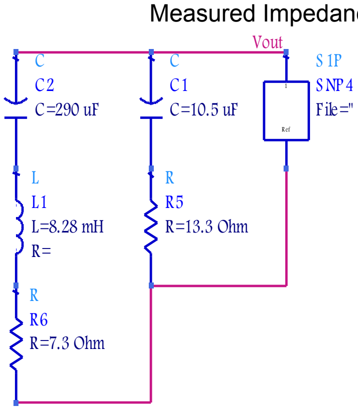
Tweeter Measured Impedance

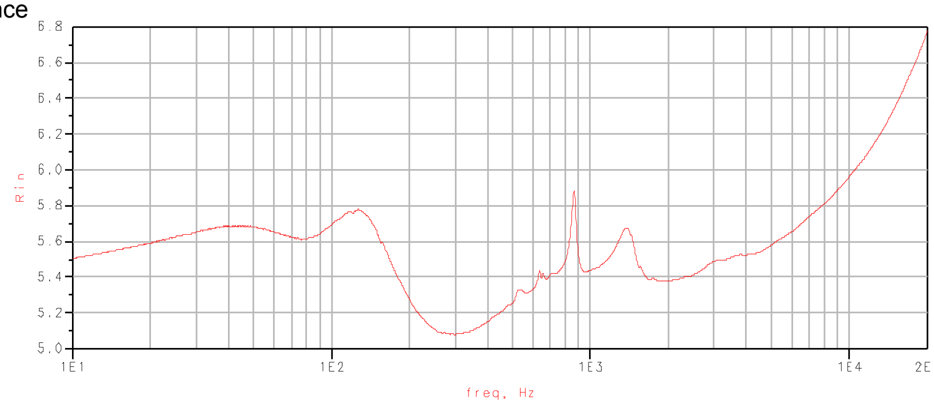




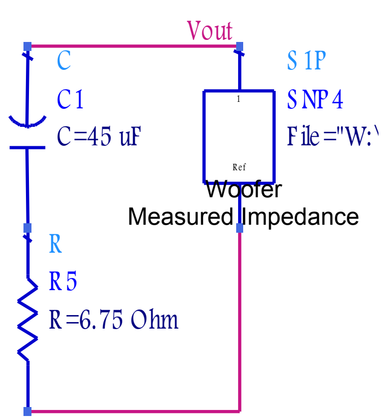
Midrange

Midrange
Measured Impedance

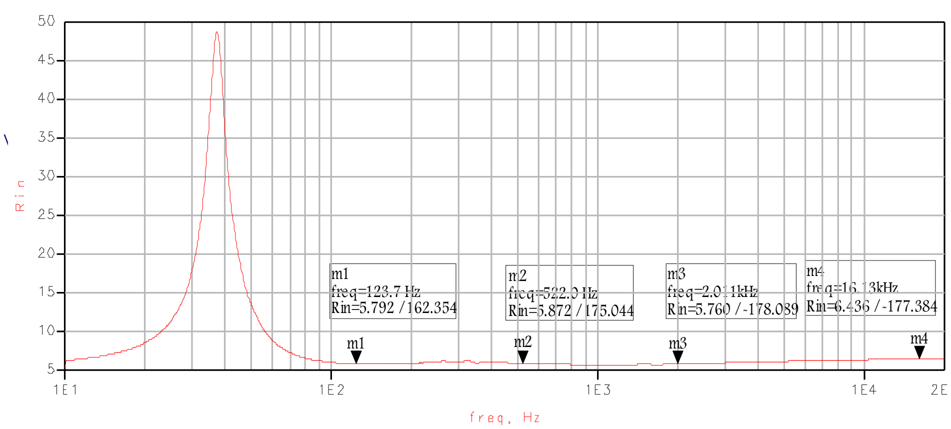




Woofer

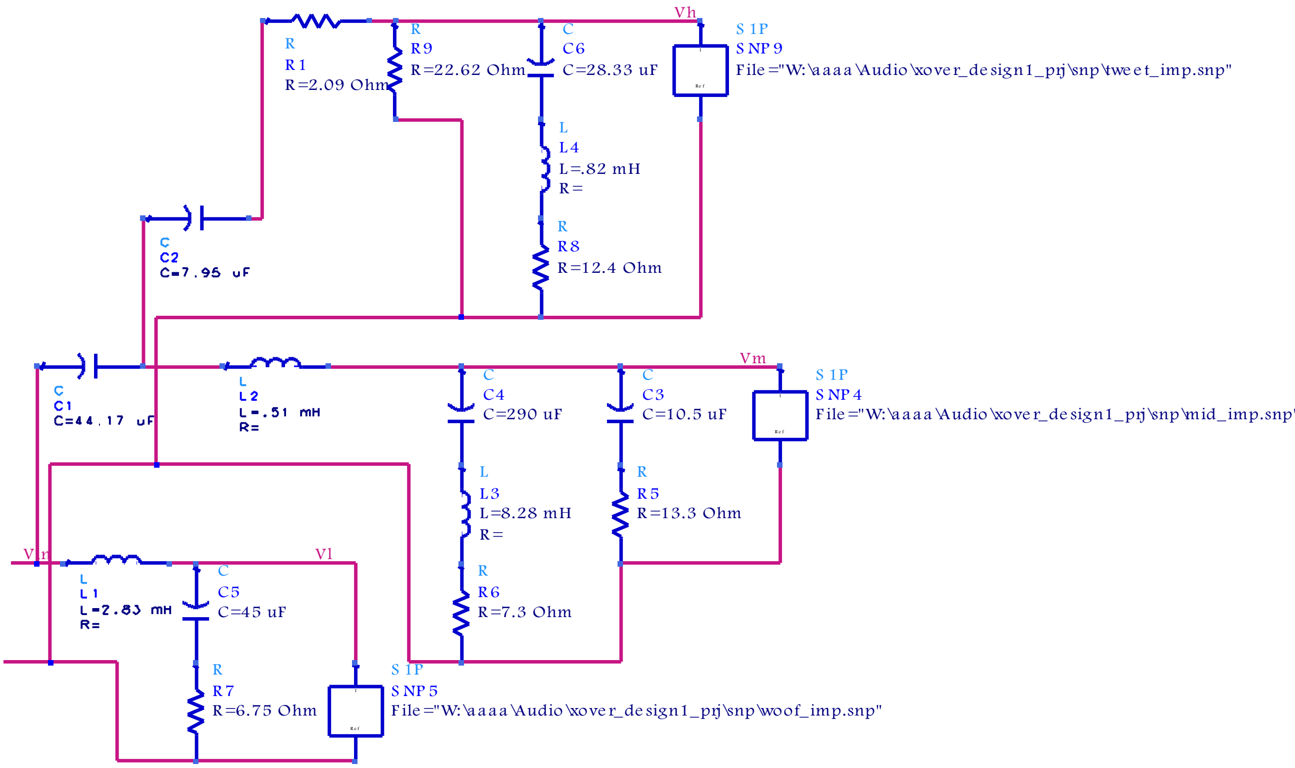


Woofer
Measured Impedance

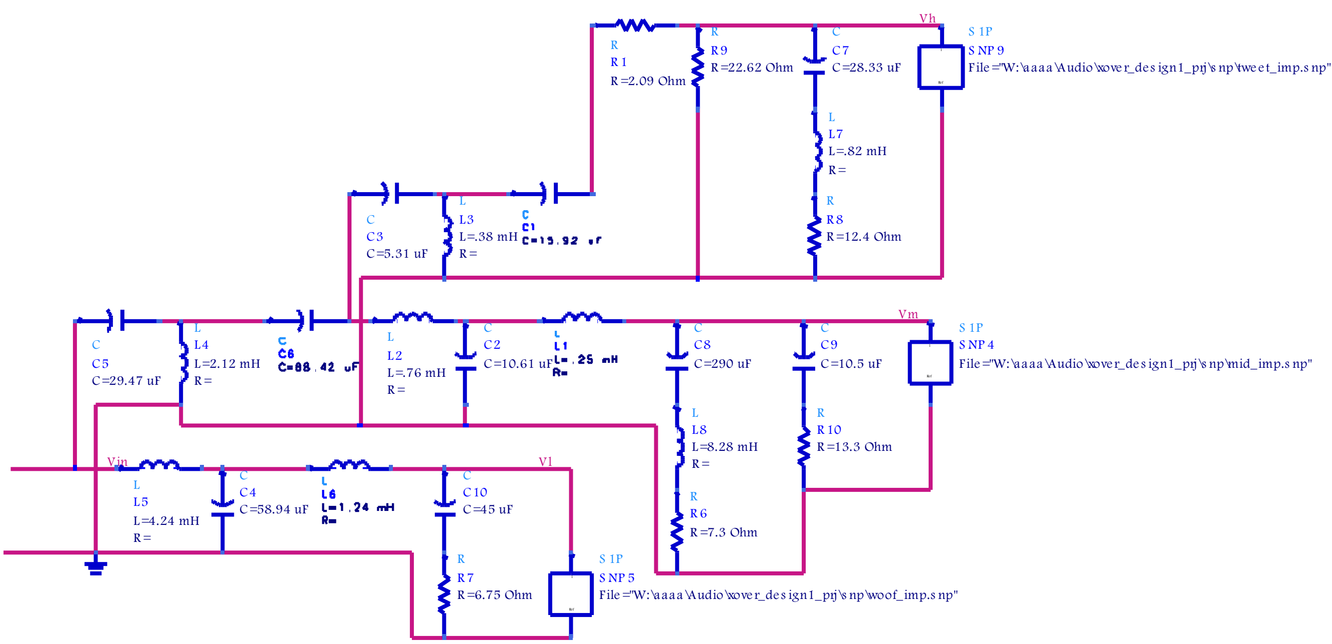


APPENDIX 8. CROSSOVER CIRCUITS

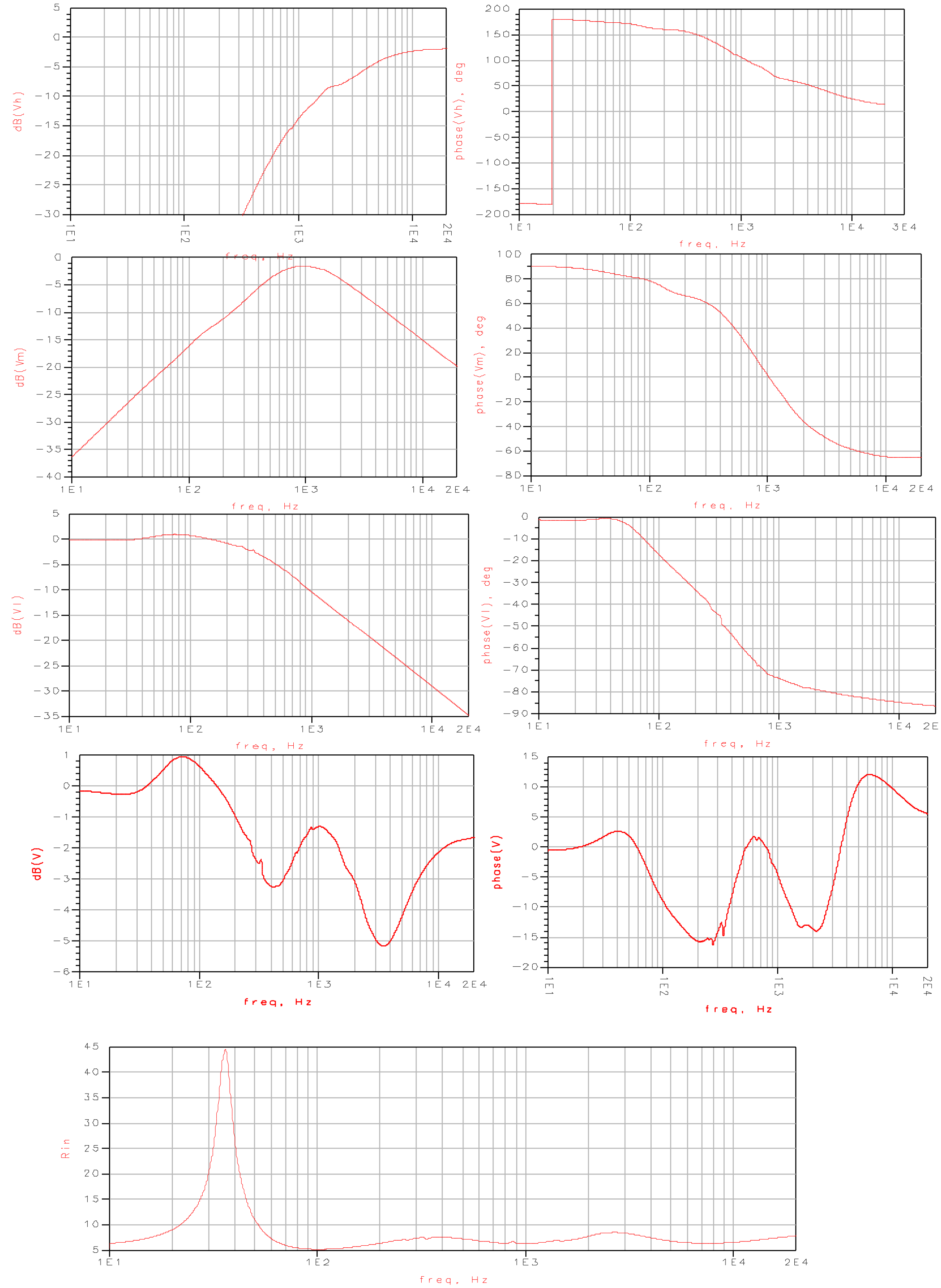
1st order at 450Hz and 1st order at 2500Hz crossover circuit:



3rd order at 450Hz and 3rd order at 2500Hz crossover circuit:



1st order at 450Hz and 1st order at 2500Hz crossover simulation:



REFERENCES

[1] Small, Richard, "Direct-radiator loudspeaker system performance," Audio Engineering Society, June, 1972.

[2] "The Subwoofer DIY Page"http://www.spiceisle.com/audiodiy/sld/sealed.htm

[3] E. Jakulis, "Group Delay," http://www.feist.com/~nihil/groupdelay.html.

[4] J.L. Murphy, True Audio, "Loudspeaker Diffraction Loss and Compensation," Jun 20, 2000, http://www.trueaudio.com/st_diff1.htm.

[5] J. K. Iverson, "The theory of loudspeaker cabinet resonances," Audio Engineering Society, April, 1973.

[6] J. D'Appolito, Testing Loudspeakers. Peterborough, New Hampshire: Audio Amateur Press, 1998, pp. 9-89

[7] J.L. Murphy, True Audio, "Neutralizing L(e) with a Zobel Jun 22, 1997," Jun 22, 1997, http://www.trueaudio.com/st_diff1.htm

[8] E. Baekgaard, "A novel approach to linear phase loudspeakers using passive crossover networks," Audio Engineering Society, May, 1977.