The Ultimate Loudspeaker Design

TQWP

Mike MacLeod

The Ultimate Loudspeaker Design

A design and construction manual.

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Technical:

Introduction To Capacitors
The Lost Art of Loudspeaker Design
Constructors Mate
Map Reading and Navigation for Everyone

Novels:

Ride The Restless Wind
A Fools Gold

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Chapter 1

Horns and Pipes.

This is a story of Two and a Half men, no I'm only joking. It does however revolve around the work of two men from the 20' and 30's.

Have you ever taken notice of horned instruments like trumpets, trombones, French horns etc; they're basically a long flared pipe that gets wider and wider along its length. This allows the sound to be amplified and travel some distance. Well, a guy by the name of Paul G.A.H. Voigt studied this phenomena back in the 1930's and came up with a loudspeaker of similar proportions called a tapered quarter-wave pipe or TQWP for short. He found that by closing one end of the pipe and placing the speaker at a pre-determined point from the closed end, he could get a very natural sound with plenty of midrange grunt and a relatively lively bass. The fundamental length of the horn is determined by the quarter wavelength of the speed of sound and the resonant frequency of the box. A surprise feature of his design was that the speaker was placed on the side of the box. He came up with several formulae to determine this point and the following two work well:

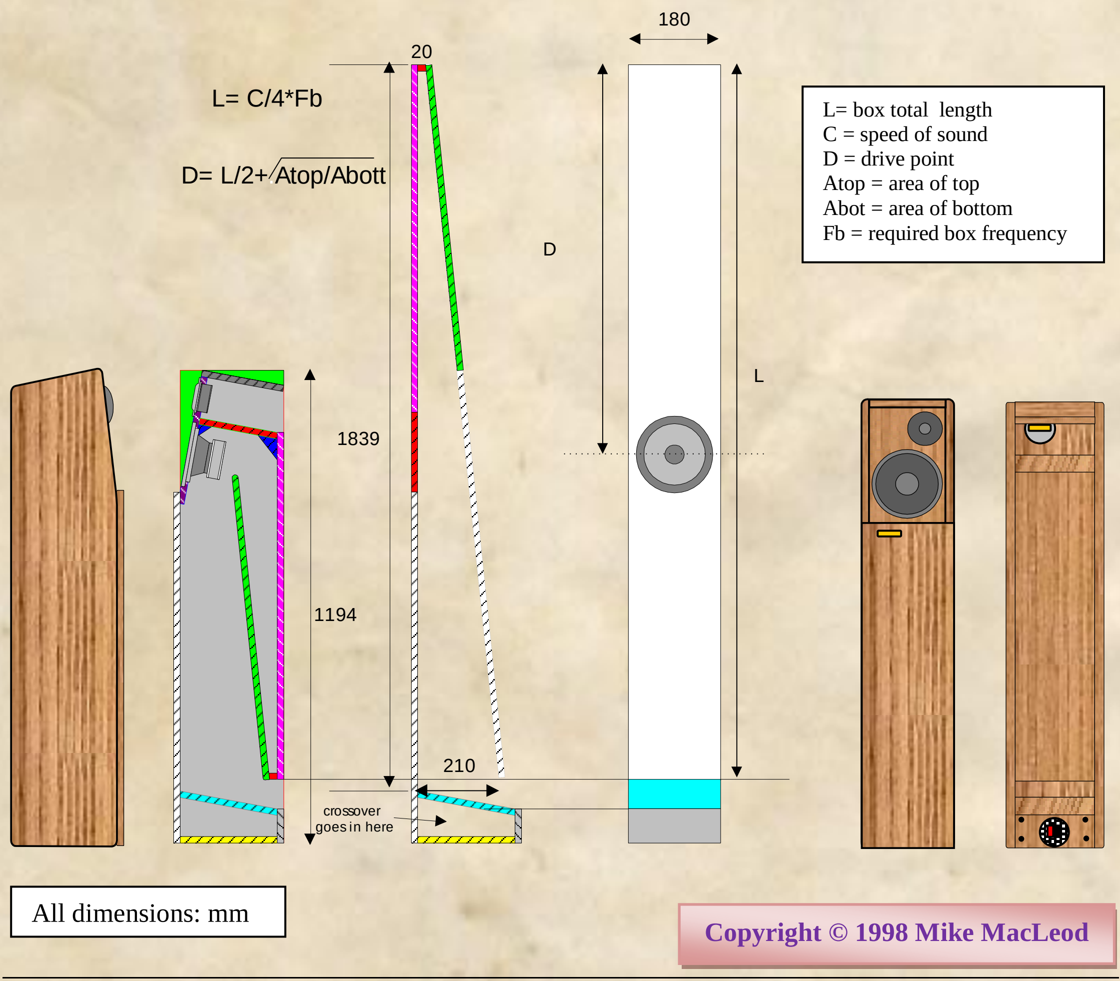
$$L = (C / 4F_b)$$

$$D = \frac{L}{2 + \sqrt{A_{top} \div A_{bot}}}$$

The picture on the right is a typical example of a Voigt pipe standing almost 2 m tall. Usually a full range speaker is fitted with no crossover. My starting point was the availability of loudspeaker drivers and the most popular ones are those with yellow fibre glass cones and rubber surrounds and are relatively cheap. It has been found through experiment that 6.5 inches is the optimum size and not wanting to reinvent the wheel, I followed the general consensus.

There was only one problem, the wife. No way was she going to allow these ‘monstrosities’ in the lounge and I would be banished to the study which was tiny and cramped and had no sound qualities at all. If you have read my book ‘The lost Art of Loudspeaker Design’ you will remember that I used the Golden Ratio to size my lounge which had excellent acoustic properties. So what now. Then I remembered reading Viv Capel’s book on speaker design. It had a labyrinth speaker of quite small dimensions with internal baffling to give it a longer internal length.

So I sat down at my computer and used Visio 3.0 to try and design a compromise box by folding it in half, which I succeeded in doing, see drawing below.



1

When drawing up the design criteria for this project, I decided that I would add a tweeter to the box using a second order 2-way Butterworth crossover. This brings us to another gentleman, also from the 1920's, one Mr Otto Zobel, who worked at Bell Laboratories. He studied filters for telephone lines and came up with a bunch of formulae for various types of equipment. By the way, you can try Wikipedia for more info on these gentlemen. Now what made his work significant was that by marrying his filters with the standard text book crossover filters, created the 'Super Filter'. But wait there's more...

I have a penchant for collecting magazines and collected a whole lot of 'Electronics, The Maplin Magazine' and much to my surprise found an interesting article on a subwoofer design for a car. What piqued my interest though was the detailed mathematics involving Zobel filters and how to apply them to Audio Systems, but at the time it went way over my head. But being the obstinate person that I am, I locked myself in my house for a few days until I cracked it. Eventually I managed to see what was going on (the author of the article was probably a mathematical genius and wrote from the point of view that he was addressing some undergraduate students). Sorry I only got woodwork and sums at school, so I rewrote the formulae that applied to my work and must say that I think this is the ultimate crossover network, so a sincere thanks to Mr. J. M. Woodgate B.Sc.(Eng.),C.Eng.,M.I.E.E., F.A.E.S.,F.Inst.S.C.E. and I have been using it in my personal Hi- Fi ever since 1998 and now make it available to you.

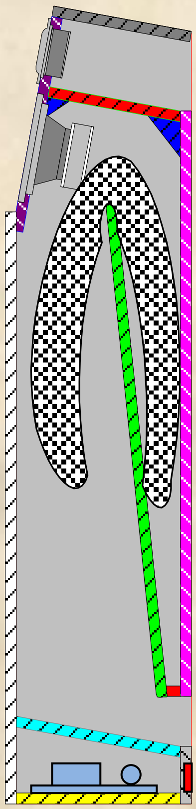
I have always been a fan of Bang and Olufsen and I have studied their work into phase distortion which is a result of the axial misalignment of the tweeter and woofer voice coils. Having solved this problem as indicated in my book 'The lost Art of Loudspeaker Design', I was keen to implement something similar into the current design. I positioned the two drivers in such a way that their voice coils were equidistant from a fixed reference point ahead of the box and that is why the top portion of the box is angled.

Okay, getting back to the speaker, I found that it had a hole in the magnet, I guess for cooling and after several experiments found that it performed better with the hole plugged. The initial resonant frequency was 44.5 Hz and on reflection maybe one with an F_s of about 120 Hz would do, but I have kept the original ones. Taking the formula for the length of the cabinet, I aimed at a box frequency, F_b of 45 Hz and the speed of sound as C = 331m/s (I live at 5200 foot asl), and plugged this into the formula:

$$L = \frac{331}{4 \times 45} = 1839 \text{ mm}$$

So this was the starting point for shaping the cabinet. The width of a 6.5 inch speaker is about 165mm and gave me a width for the speaker of 180mm. Taking the top as 20mm and the bottom as 210mm I plugged this into the second formula to calculate the drive point of the speaker and came up with the following:

$$D = \frac{1839}{2 + \sqrt{(20*180) \div (210*180)}} = 796 \text{ mm}$$



I wanted the crossover separate from the box, so I added a compartment to its base. Another requirement is that the box must be 'stuffed' to dampen the speaker. This requires the fitting of dampening material inside the enclosure but what I did was buy a metre of 'duvet' filler, about 20mm thick and about 1.8m wide. I then rolled this up into a sausage 1m long and pushed it into the box through the speaker opening so that half of it went down the enclosed end and the other half hung into the open end.

The port area is equal to the cone area of the woofer. Also notice that the front panel of the box sticks out, this is to allow the fitting of a speaker grill which would then blend with the step. The grill is simply a frame made from 10mm x 10mm pine and covered with speaker cloth. It can be attached to the speaker with small squares of Velcro tape glued onto the corners of the grill frame and the corresponding place on the speaker box. I placed the tweeter off axis and is to the right for the right hand speaker and to the left for the left hand one. This is also a tweak to lessen the phase distortion. Another feature of these speakers is that they have a sound stage wider than the speakers themselves, adding to the realism of the performance.

1

Summary

1. A TQWP design folded in half for optimal use in small rooms.
2. Reproduces the midrange frequencies with astonishing realism.
3. Has a tweeter with a second order Butterworth filter.
4. Crossover installed in its own compartment.
5. Port area equal to speaker cone area.
6. Enclosure filled with stuffing to dampen the loudspeaker cone.
7. Tweeters mounted off axis.
8. Sound stage wider than the speaker themselves.
9. Recommended amplifier power, 80W RMS. Output level dependant on speaker sensitivity.

Chapter 2

Zobel Networks.

The latest midrange and tweeter loudspeakers utilize dome technology i.e. they don't use paper cones but rather soft textile or titanium/aluminium diaphragms and because of this they sound harsh at their fundamental frequencies, as they act more like woofers due to their very low resonance, which disturbs the crossover network. This is because these frequencies fall within the crossover region and upset the networks' balance, causing annoying resonance. Mids and tweeters that are ferro-fluid cooled don't suffer as much from this phenomenon because the fluid acts like a mechanical damper giving them smoother responses, but unfortunately not all of them are cooled this way.

Looking at the woofer impedance graph, in Figure 8, you will note two things. One, the resonant peak is high at resonance, usually below 100 Hz. and two, as the frequency rises so does the impedance, as shown by the impedance curve gently rising upwards on the right hand side of the graph from about 100Hz and up. Now for low sounding bass this peak is all right but it would also be nice if the woofer curve could stay flat after the resonant peak, increasing its efficiency, which is compromised by the increase in the speaker's voice coil inductance.

As I alluded to earlier, the crossovers are very trick ones indeed and after much study and reworking I came up with my own formulae and this is what you will find in the charts below. They are my copyright and hope that you will regard them as not for general public consumption and for your own private use only – I mean we want the best for ourselves and not some foreign Far East company to mass produce in some cheap and nasty system as they usually do.

Taking our tweeter as an example, we need to prevent the rise in voice coil inductance and to this end we use an impedance equaliser, consisting of a resistor R1 in series with a capacitor C5 both in parallel with the speaker. See Figure 1. What this in effect does is to make our loudspeaker load purely resistive resulting in a flatter impedance curve and the value of R1 is usually equal to R_e, the voice coil dc resistance as measured with a multimeter. The formula for the capacitor is:

$$C5 = \frac{L_e}{(Re)^2}\ \mu F \qquad R1 = R_e\ \Omega$$

To calculate L_e we need to measure the frequency F5, see Fig 6. I prefer to calculate L_e as one cannot be too sure of the manufacturer's data. Be sure to record F5 correctly and is usually found way above the resonant frequency, between 300 and 1000Hz. Also record all data under "Zobel Parameters" on the data sheet. For the bass driver that is all we need to do. For the tweeter we have to add a resonant peak filter consisting of R2, C6 and L5, which removes the annoying peak, giving a flatter overall response. Refer to Figure 2 for the schematic layout. Following this we move onto the charts for calculating component values for the crossover. Note that the formulae are for a Butterworth filter which has a different characteristic to that of the Linkwitz/Riley network, resulting in slightly different values. Butterworth = 0.707/1.414 while Linkwitz/Riley = 0.5/2.0 and Bessel = 0.57/1.74.

You will also see that in the formulae, we use the dc resistance of the voice coil and not the impedance at the crossover frequency, as we did for the text book formula when calculating the capacitance and inductance. This is because the Zobel network makes the speaker load purely resistive (the speakers dc resistance as measured with a digital multimeter) and constant over the crossover region, allowing the crossover network to perform at its optimum efficiency. See Page 24 for a sample sheet of the calculations for the woofer.

Use the same procedures and precautions when assembling the crossovers by referring to Chapter 4 of 'The lost Art of Loudspeaker Design'. The Zobel networks fit in-between the normal crossover network and the speakers, see Fig 2. By the way the reason for the component numbering in Fig 1, is that it is the same as a 3-way crossover but with the midrange part omitted and thus the numbering is not consistent. An Exel spreadsheet as well as a full set of plans are available. See website for details.

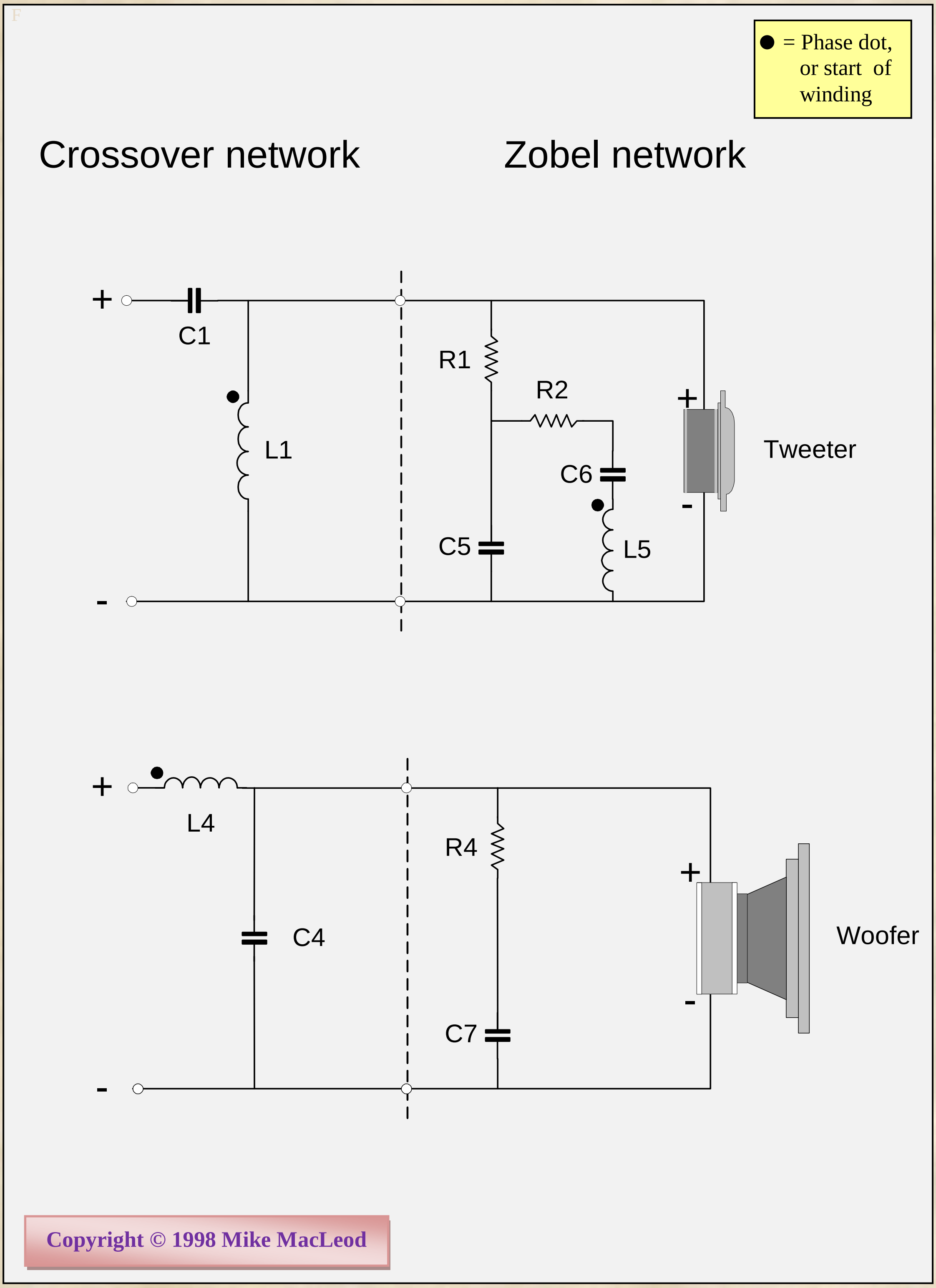

● = Phase dot, or start of winding
Crossover network
Zobel network
+
C1
L1
-
R1
R2
C6
L5
C5
+
-
Tweeter
+
L4
C4
-
R4
C7
+
-
Woofer
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Fig 1

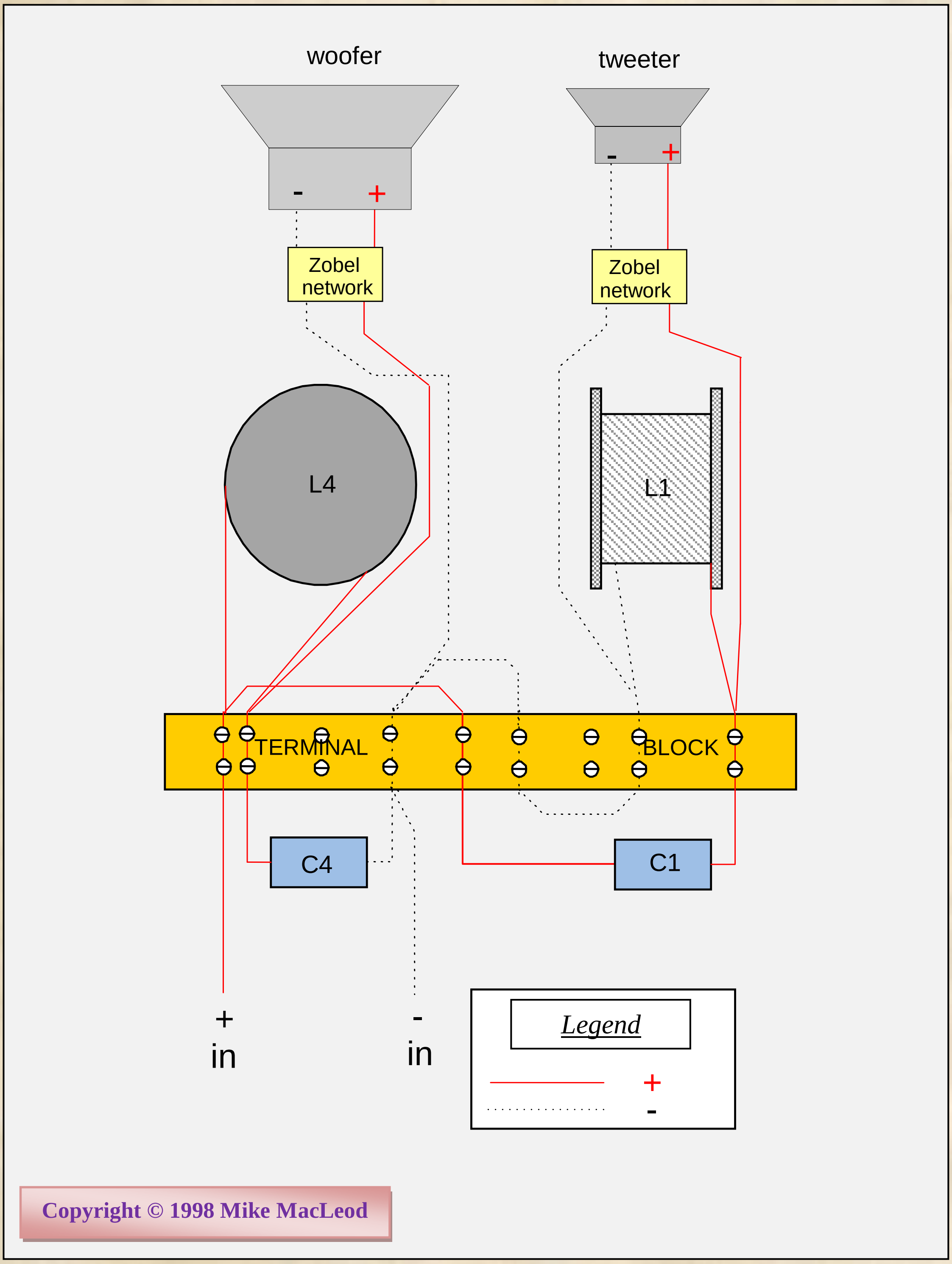
woofer
tweeter
-
+
-
+
Zobel network
Zobel network
L4
L1
TERMINAL
BLOCK
C4
C1
+
in
-
in
Legend
+
-
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Fig 2

2

<u>Summary</u>

1. Zobel networks are used to control the peaks of dome type speakers.
2. They are also used to curb the impedance rise in woofers.
3. They stabilise the crossover network, resulting in optimal performance.
4. Use 5watt wire wound resistors in the networks.
5. Make sure the voltage rating of the capacitors is high enough. (See the table on page 54 of ‘The lost Art of Loudspeaker Design’).
6. Connect a 100 nF cap in parallel with bipolar ones to lower the ESR, but watch its voltage rating.
7. Coils are all wound in same direction starting at the same side of coil former – see phase dots on schematic diagram. Phase dot equals the start of a winding.
8. Mount adjacent coils at right angles to each other with sufficient space between them to prevent magnetic interaction, by hot glueing them onto a thin piece of ply wood.
9. Use white 2 core cabtyre ‘extension cable’ for hook-up wire.
10. As usual, all measurements are in mm and internal ones.
11. Place your speakers in the corners of the room to make use of the horn effect for good bass response.
12. For the pundits out there wondering why the tweeter is connected with normal phasing, it’s because the frequency has been manipulated -6dB down at the cut-off point (the $\sqrt[4]{3}$ term in the equations) rather than the usual -3dB, thus keeping the tweeter in phase.

Chapter 3

Test Setup

Okay, now that you have obtained your prized speakers, the fun begins. Each speaker cone has a natural tendency to resonate, that is, it vibrates at a maximum rate at a specific frequency when it has a signal applied to it.

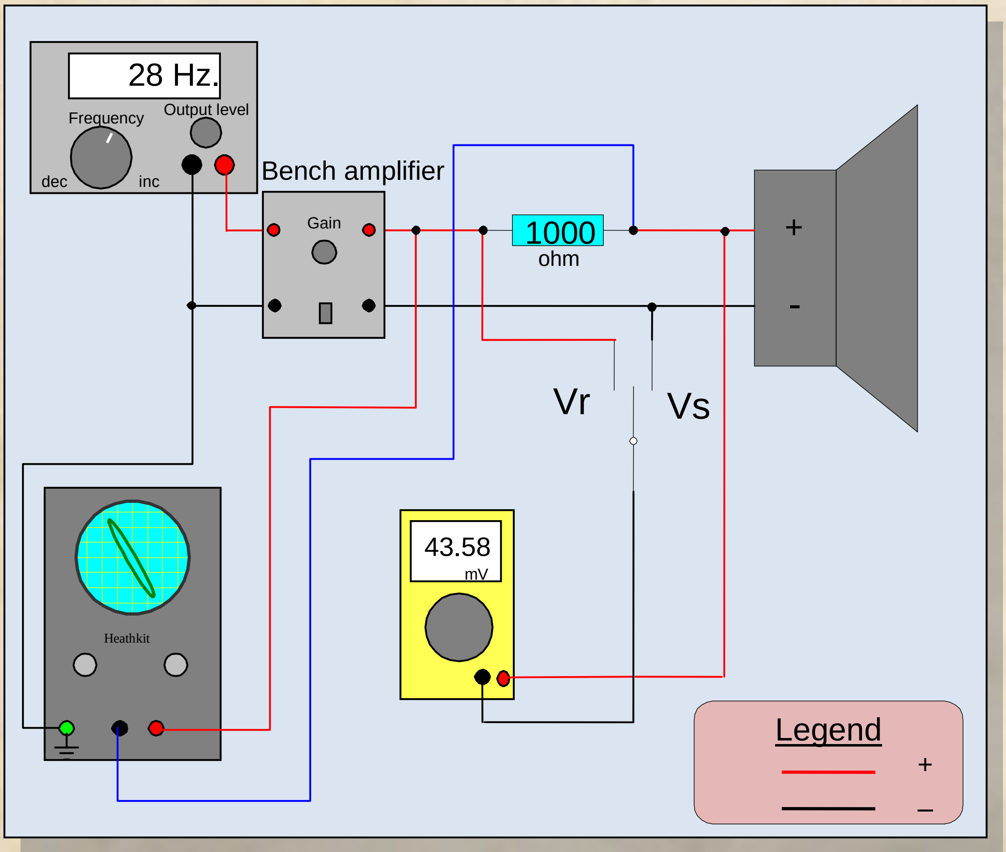


Fig 3. *Test setup.*

The frequency where this maximum resonance takes place is known as the speaker's **resonant frequency, F_s**. To do all your measurements, you will need a voltmeter, sine wave audio generator with variable voltage output and a frequency meter. I add a bench amp to help boost the power. Connect your speaker up as per Fig 3. You could make up a box with phono sockets and the switch fitted, and then wire in the 1000-ohm resistor directly to the tabs, to make life easier – see Fig 4 below.

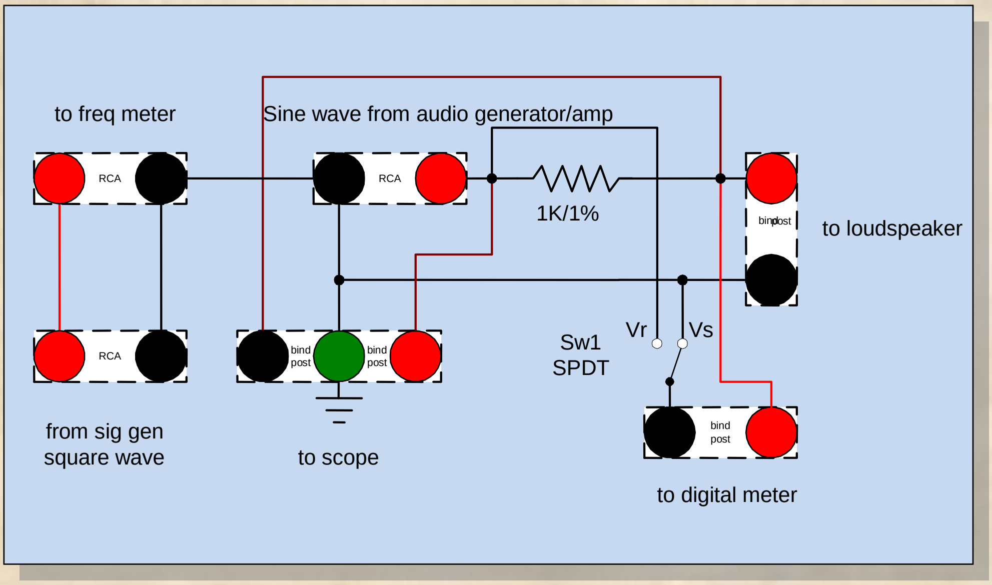


Fig 4.

With everything switched on, sweep the audio generator up and down to ensure that everything is working properly and that there is a reading on the voltmeter - you can also feel the loudspeaker cone vibrating. I prefer a DMM here because it's easier to read. Note the switch positions marked $\mathbf{V_R}$ and $\mathbf{V_S}$ in the diagram, one measures the voltage across the resistor and is measured in Volts and the other measures the voltage across the speaker and is measured in milliVolts. To determine the impedance you divide V_S by V_R :

$$\text{Speaker impedance in ohms} = \frac{V_S \text{ mVolts}}{V_R \text{ Volts}}$$

The 1000-ohm resistor sets the current level and if you ensure that V_R is equal to 1 Volt at each measurement, this is important because the voltage varies with the change in frequency, then your multimeter will read the impedance directly. If your audio generator output level cannot be adjusted then you will have to manually work out the impedance with the above formula. To measure the resonant frequency, don't believe the manufacturers figures, you test the speaker in free air, that is, on its own and not in a box. The following measurements are all done outside on a clear day so that obstructions don't affect the readings. Set the audio generator to its lowest reading, say 10 Hz and place the test switch in the

V_S position, also make sure your DMM is set to ***AC milliVolts***. Now slowly increase the frequency, watching the multimeter. It will start increasing to a maximum point and then start to drop back down again. With the reading at its highest, switch the test switch to V_r and set output level to 1 volt, then go back to V_s and record the voltage and frequency displayed on the frequency counter. If you have an oscilloscope, connect the vertical and horizontal inputs across the resistor and watch for the collapse of the Lissajous circle to a flat line, showing zero phase shift.
You have now found the speakers resonant frequency, **F_s**. Look at the sample "Impedance data chart", **Fig 5** below and set each frequency, making sure that V_R is 1 Volt and record the impedance reading on the

Impedance data chart

FREQUENCY HZ.	**V_S mVolts.**	**V_R Volts.**	**IMPEDANCE- Z_{fs} Ohms.**
10	13.3	1.256	***10.58***
15	19.7	1.147	***17.17***
20	26.2	1.038	***25.24***
25	39.1	1.030	***37.96***
30	41.7	0.965	***43.21***
35	31.0	0.963	***32.19***
40	22.2	0.933	***23.79***
50	13.5	0.895	***15.08***
60	10.5	0.847	***12.39***
70	8.3	0.802	***10.35***
80	7.2	0.776	***9.27***
90	6.2	0.730	***8.49***
100	9.1	1.136	***8.27***
200	9.1	1.272	***7.15***
300	7.1	0.930	***7.63***
400	6.1	0.751	***8.12***
500	5.6	0.648	***8.64***
600	5.5	0.580	***9.48***
Resonant Frequency - F_s			
44.5	***60.05***	***0.964***	***62.3***

Fig 5.

multimeter with the switch in the V_S position or record both V_R and V_S as required, if you are doing it manually. When you have finished tabulating all the data, you can plot your impedance curve on the "Impedance Curve chart", see Fig 8. The Appendix A has all the blank forms for you to copy and fill in with your own test figures. Try holding your hand or a book just above the speaker and watch the meter readings, you will see why one does these tests outside where there are no obstructions and make sure there is *no* wind blowing. To see what I mean, gently push the cone in and out and watch the meter readings. *Note that these sample figures are from my speaker, yours will be different.*

To measure $\mathbf{R_e}$ accurately, set your digital multimeter to its lowest setting and then short your test leads together and note their resistance, mine are about 0.2Ω. Subtract this from your final readings for best accuracy, especially on readings below 10Ω.

The resonant frequency, $\mathbf{F_s}$ and its impedance $\mathbf{Z_{fs}}$, is taken from the chart in Fig 5. Calculate **Z'**, which is 62.3 x .707 = 44.05 ohms. Set the resonant frequency on the audio generator and then slowly increase it until the DMM reads 44.05 and record this frequency as F_1. Now slowly decrease the frequency below resonance until again you get 44.05 on the DMM and record this as F_2. At the bottom of the chart is a formula for checking $\mathbf{F_s}$ using F_1 and F_2 and the result should be within ±1 % of each other. Notice that I write all the important figures that I use to either make the crossovers or for use in other formulas in **red**, this makes them stand out and makes them easier to see on a page full of data.

The following terms are used:

- R_e = Is the D.C. resistance of the coil measured with a multimeter.
- F_s = Speaker resonant frequency.
- Z_{fs} = Impedance at resonance.
- Z_{f3} = Is 0.707 of the value of Z_{fs} – the 3dB points.
- F_1 = The frequency above F_s where the impedance equals Z'.
- F_2 = The frequency below F_s where the impedance equals Z'.
- Q_{ts} = Total Q of the speaker.

Summary:

1. Do all speaker measurements outside in still air, clear of any obstacles.
2. Make a jig to hold the speaker vertically when doing the tests so that the sound wave isn't reflected back at the cone as would happen if laid flat on a table.
3. $\mathbf{V_R}$ measures the voltage across the resistor and is measured in Volts
4. $\mathbf{V_S}$ is measured in milliVolts and measures the voltage across the speaker.

Chapter 4

TYPE : … Noname …. **P/N** : …….902.423……… **DATE** : ……07/3/1998…...

	LEFT HAND	**RIGHT HAND**
Woofer parameters : R_e F_s Z_{fs} Z_{f3} F_1 F_2 F_3 F_4 Q_{ts}	……7.2…….. Ohms. …….44.5……. Hz. …….62.3……. Ohms. …….44.05….. Ohms. ……..51…….. Hz. ……39…….. Hz. ……..75.2……. Hz. ……..38.1……. Hz. ……0.41..	………………… Ohms. ………………… HZ. ………………… Ohms. …………… Ohms. …………… Hz. …………… Hz. …………… Hz. …………… Hz.
$\mathbf{Z_{fs}} = \frac{V_s}{V_r}\ \frac{mV}{V}$ $Z_{f3} = .707 \times Zf_s$ F_1 & F_2 is the frequency of Z_{f3} above & below F_s.	$\frac{62.3}{1}$ = Z_{fs} = …62.3..Ohms. Z_{f3}=.707 x 62.3 = 44.05 Ω	________ = Z_{fs} = ……...Ohms. Z_{f3}=.707 x …… = ……...Ω
Speaker Q: $ro = \frac{Z_{fs}}{R_e}$ Rref $= \sqrt{ro} \times R_e$ Ω for recording F3 &F4. $\mathbf{Q_{ts}} = \frac{F_s}{F_3 - F_4} \times \frac{R_e}{Z_{fs}} \times \sqrt{ro}$	ro = $\frac{62.3}{7.2}$ = 8.65 $= \sqrt{8.65} \times 7.2$ = **21.8** Ω $Q_{ts} = \frac{44.5}{75.2-38.1} \times \frac{7.2}{62.3} \times \sqrt{8.65}$ Q_{ts} = ……0.41……….	ro = ______ = ……………. =√………. x ……..=………. Ω Q_{ts} =____ x _____ x √………. Q_{ts} = …………………….
Check $\mathbf{F_s}$: (±1 %) $\mathbf{F_s} = \sqrt{F_1 * F_2}$ Hz	√..51...x..39.. = ..**44.59**..Hz	√……….x……… = ……….Hz
Max Output. SPL =10LOG(P) + S P= rms watts. s=sensitivity.dB@1m/1w	=10LOG...100....+...89........ =……..**109**………. dB SPL.	=10LOG…………+…………. =……………………..dB SPL.
Calculate $\mathbf{F_5}$: L_{ref} = Re x √2 Find L_{ref} above F_s and record F_5.(300-1000 Hz.)	= ..7.2.. x √2. = .**10.18**.. Ω F_5 = ……**918**….. Hz.	= …… x √2. = ……… Ω F_5 = ……………. Hz.

Fig 6

Chapter 4

Fig 7

Woofer Crossover Calculation Chart - Zobel/Butterworth.

Zobel Network: Date: …07/3/1998….

R_4 = …**7.2**.….Ω **C_7** = ….**24.08**….µF

R_e = .….7.2.….Ω **F_5** = ……918……Hz. **L_e** = ……1.25…..mH.

$$L_e = \frac{R_e}{2 \times \pi \times F_5} = \frac{7.2}{2 \times \pi \times \ldots 918\ldots} \times 10^3 = \ldots 1.25\ldots \text{mH}$$

$$C_7 = \frac{L_e}{{R_e}^2} = \frac{1.25}{(7.2)^2} \times 10^3 = \ldots 24.08\ldots \mu\text{F}$$

$$R_4 = R_e \quad @5\text{watt} \qquad = \ldots 7.2\ldots \Omega$$

Crossover Network:

Crossover point: F_{lo} =...**2500**…Hz.

L_4 =....**0.85**…..mH **C_4** = …**8.23**…µF

Frequency factor $\omega_{lo} = 2 \times \pi \times F_{lo} \times \sqrt[4]{3} = 4.77 \times \ldots 2500\ldots = \ldots 11935\ldots$

$$\chi = \frac{\sqrt{2}}{2} = 0.707$$

$$C_4 = \frac{\chi}{R_e \times \omega_{lo}} = \frac{0.707}{7.2 \times 11935} \times 10^6 = \ldots 8.23\ldots \mu\text{F}$$

$$\lambda = \sqrt{2} = 1.414$$

$$L_4 = \frac{\lambda \times R_e}{\omega_{lo}} = \frac{1.414 \times 7.2}{11935} \times 10^3 = \ldots 0.85\ldots \text{mH}$$

4

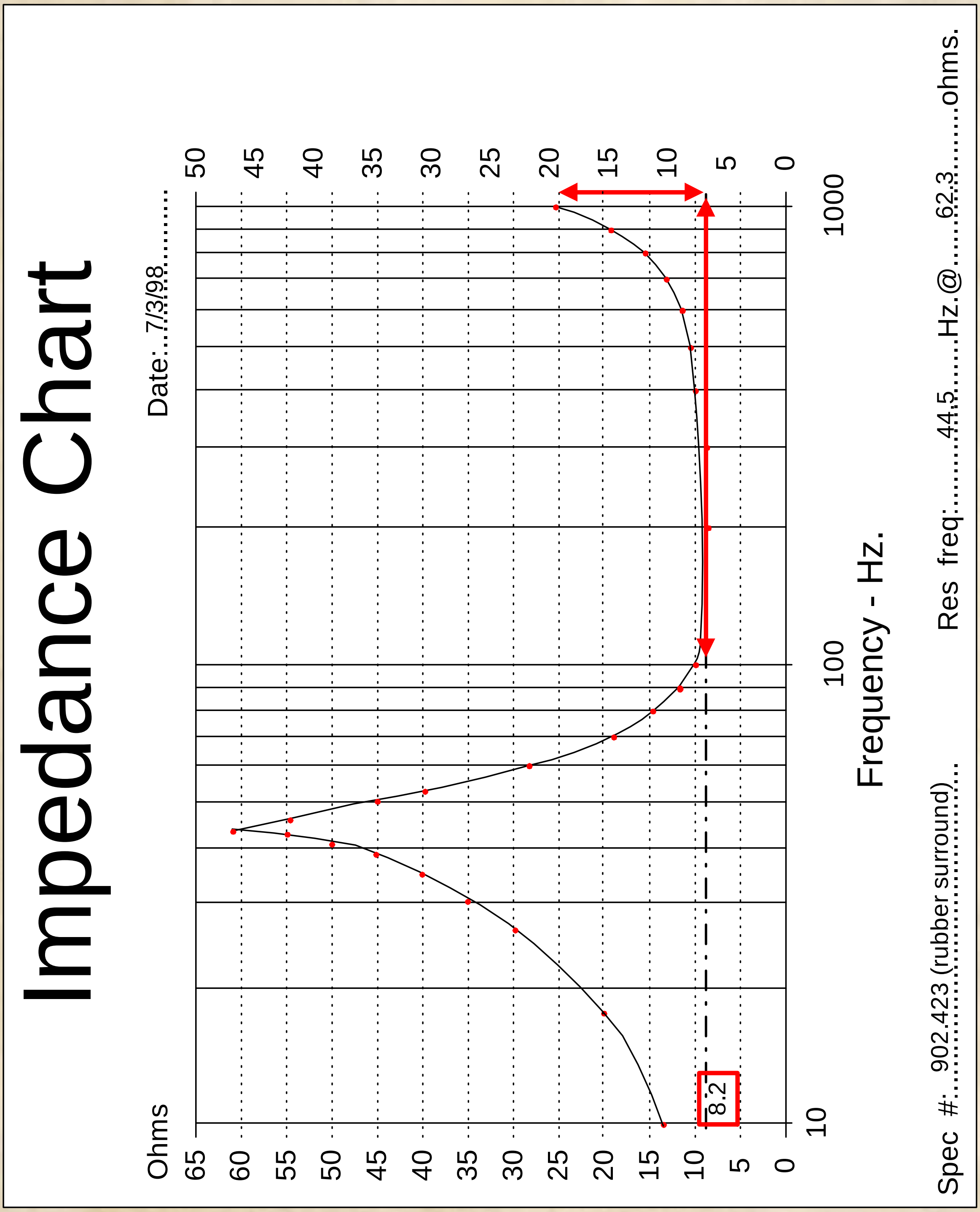

Impedance Chart
Date:...7/3/98........
Ohms
65 60 55 50 45 40 35 30 25 20 15 10 5 0
50 45 40 35 30 25 20 15 10 5 0
8.2
10
100
1000
Frequency - Hz.
Spec #:....902.423 (rubber surround)........
Res freq:.........44.5.......Hz.@.....62.3........ohms.

Fig 8

Crossover Parts List.

+ = series connection. * = parallel connection.

crossover point = ………2500……..…Hz.

Tweeter: C1 = …..…..…μF = ……..…@……..…v …….……@……….v

C5 = ………...μF = ……..…@……..…v ……….…@……..…..v

C6 = …………μF = ……..…@………..v ………….@…..……v

R1 = ……..…..Ω = ………. ………….

R2 = …………Ω = ………. …………

L1 = …………mH

L5 = ……….…mH

Woofer:

C4 = …**6.25**....μF = …**4.70**…@...160....v * …**2.2**…..@…160.…v

C7 = …**24.08**..μF = ….**22**….@…160.…v * …**2.2**..…@....160....v

L4 = …**0.65**....mH

R4 = …**7.2**……..Ω = …**3.9**..… + ….**3.3**..…

Note: Use higher voltage caps on parallel connection.

Fig 9

Appendix A

Loudspeaker Dimensions

Woofer		
Outside diameter	W_{diam}	………..mm.
Woofer radius	R_w	………..mm.
Magnet radius	r_w	………..mm.
Woofer height	H_w	………..mm.
Cone depth	W_{cone}	………..mm.
Flange thickness	W_{flange}	………..mm.
Flange width	W_{rebate}	………..mm.
Cut-out diameter	W_{hole}	………..mm.
Mounting screws		M…..

Tweeter		
Outside diameter	T_{diam}	………..mm.
Magnet radius	R_t	………..mm.
Cone depth	T_{cone}	………..mm.
Flange thickness	T_{flange}	………..mm.
Flange width	T_{rebate}	………..mm.
Cut-out diameter	T_{hole}	………..mm.
Mounting screws		M…..

Appendix A

FREQUENCY Hz.	V_S mvolts.	V_R volts.	IMPEDANCE Ohms.
10			
15			
20			
25			
30			
35			
40			
50			
60			
70			
80			
90			
100			
200			
300			
400			
500			
600			
700			
800			
900			
1000			
Resonant Frequency - F_s			

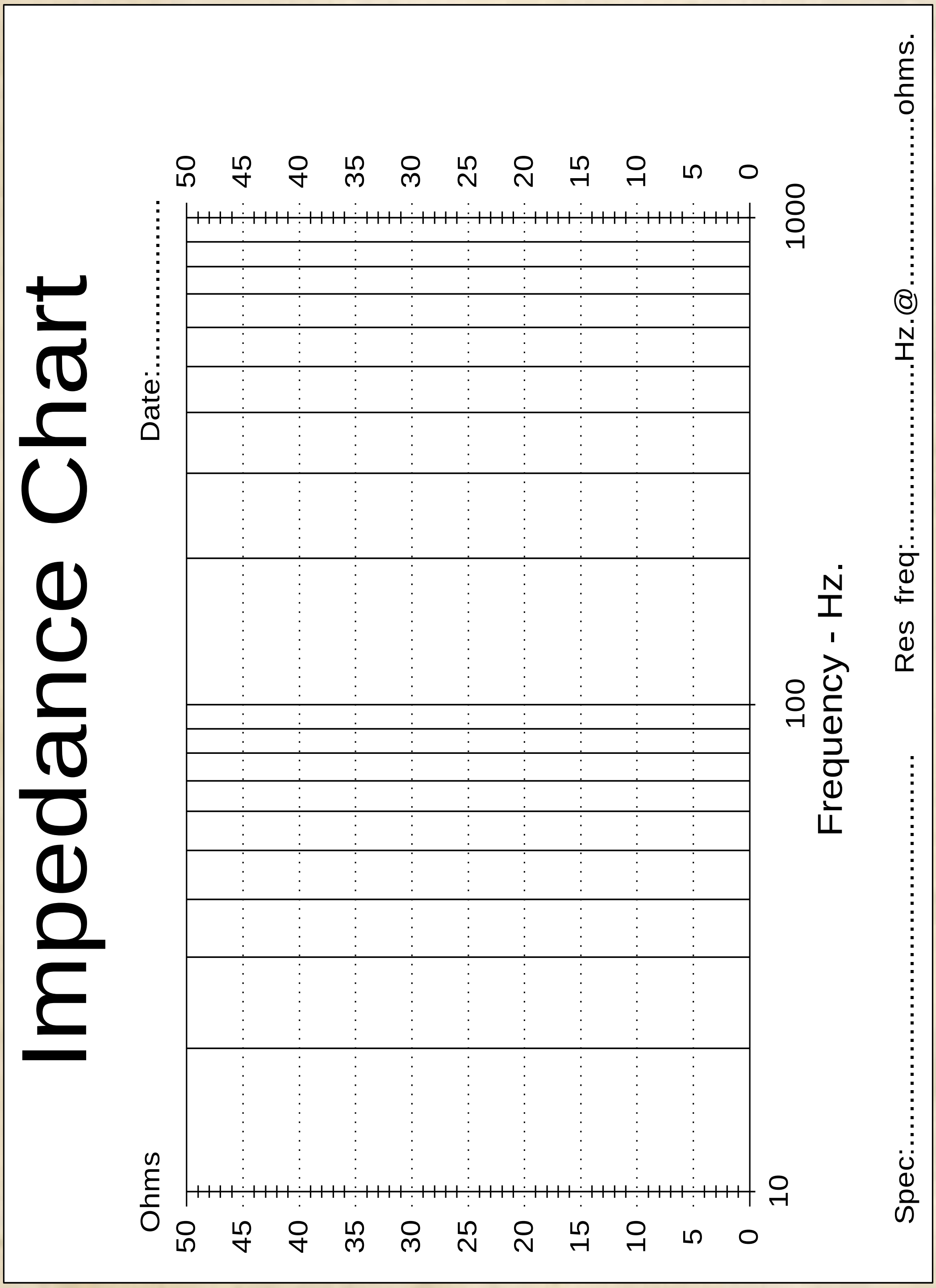
Woofer Impedance Data Chart. (Left hand)

Appendix A

FREQUENCY Hz.	**V_S mvolts.**	**V_R volts.**	**IMPEDANCE Ohms.**
10			
15			
20			
25			
30			
35			
40			
50			
60			
70			
80			
90			
100			
200			
300			
400			
500			
600			
700			
800			
900			
1000			
Resonant Frequency - F_s			

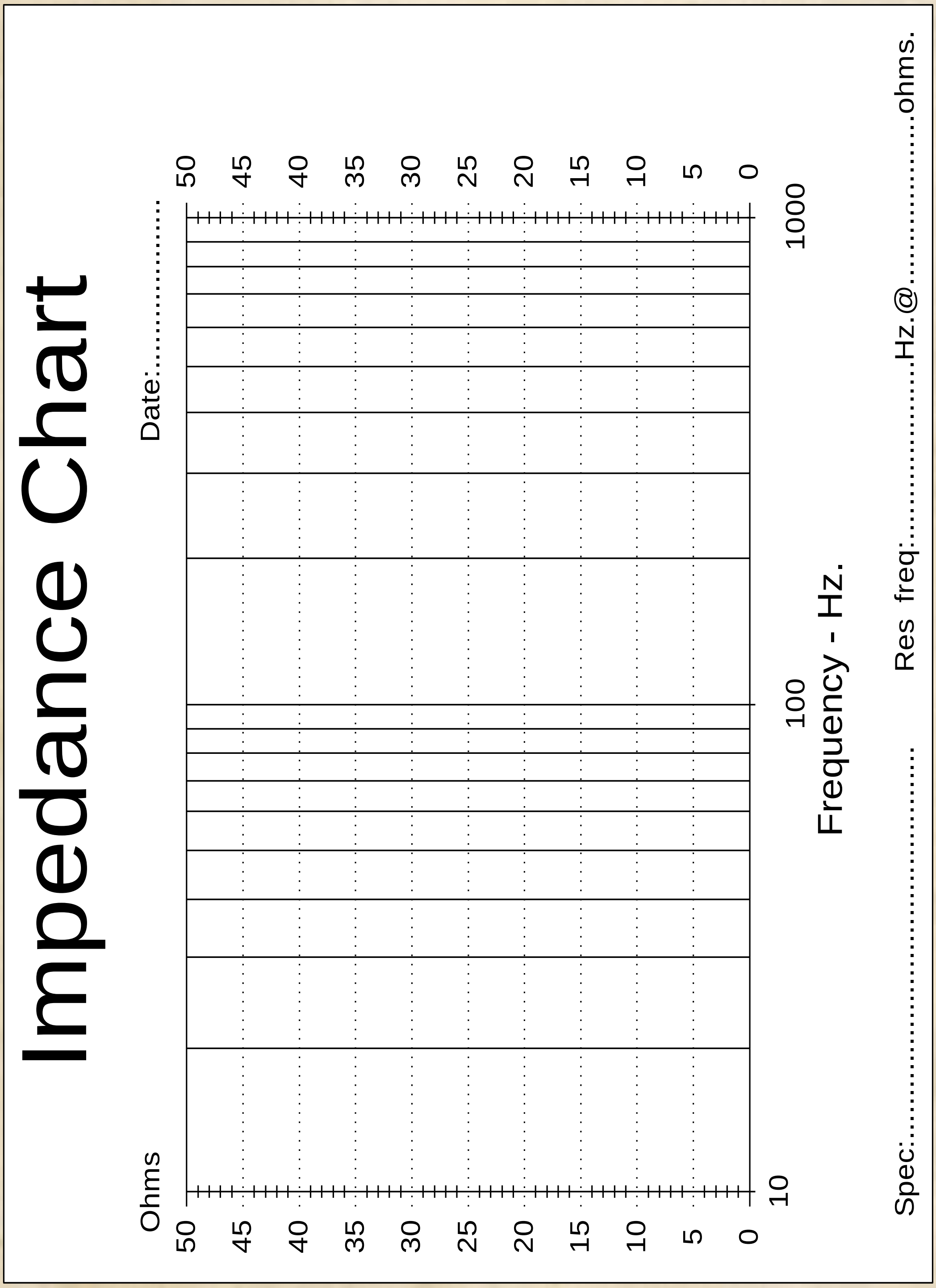
Woofer Impedance Data Chart. (Right hand)

Appendix A



<u>Woofer Impedance Curve Chart</u>. (Left hand)

Appendix A



Woofer Impedance Curve Chart. (Right hand)

Appendix A

TYPE : ………………. **P/N** : ……………………..…….. **DATE** : …………………….....

	LEFT HAND	**RIGHT HAND**
Woofer parameters : Crossover point: ……...........Hz. R_e F_s Z_{fs} Z_{f3} F_1 F_2 F_3 F_4 Q_{ts}	.... Ohms. .... Hz. .... Ohms. .... Ohms. .... Hz. ..….............. Hz. .... Hz. .... Hz. …….........	.... Ohms. .... HZ. .... Ohms. …………… Ohms. …………… Hz. …………… Hz. …………… Hz. …………… Hz. …….........
$\mathbf{Z_{fs}} = \frac{V_s}{V_r} \frac{mV}{V}$ $Z_{f3} = .707 \times Zf_s$ F_1 & F_2 is the frequency of Z_{f3} above & below F_s.	$\frac{}{1} =$ Z_{fs} = …..........Ohms. Z_{f3}=.707 x .... = ... Ω	$\frac{}{} =$ Z_{fs} = ……....Ohms. Z_{f3}=.707 x …… = …...…Ω
Speaker Q: $ro = \frac{Z_{fs}}{R_e}$ $Rref = \sqrt{ro} \times R_e$ Ω for recording F3 &F4. $\mathbf{Q_{ts}} = \frac{F_s}{F_3 - F_4} \times \frac{R_e}{Z_{fs}} \times \sqrt{ro}$	ro = ________ / .... = ... = √......... x .... = ... Ω Q_{ts} = _____ / .....-...... x ____ / .... x √....... Q_{ts} = ...….....….........	ro = _________ / .... = ... =√........... x ....=.......... Ω Q_{ts} =____ / .....-....... x _____ / .... x √.......... Q_{ts} = ...
Check $\mathbf{F_s}$: (±1 %) $\mathbf{F_s} = \sqrt{F_1 * F_2}$ Hz	√.........x......... = ...Hz	√..........x......... = ….…....Hz
Max Output. SPL =10LOG(P) + S P= rms watts. s=sensitivity.dB@1m/1w	=10LOG...100....+...89........ =......................... dB SPL.	=10LOG.............+.............. =..........................dB SPL.
Calculate $\mathbf{F_5}$: L_{ref} = Re x √2 Find L_{ref} above F_s and record F_5.(300-1000 Hz.)	= .... x √2. = ... Ω F_5 = ……......….. Hz.	= …… x √2. = ……… Ω F_5 = ……………. Hz.

Woofer Crossover Calculation Chart - Zobel/Butterworth.

Zobel Network: Date: ………………….

R_e = ..……...…Ω **F_5** = ………………Hz. **L_e** = ……………...mH.

R_4 = ………..…Ω **C_7** = ……………..μF

$$L_e = \frac{R_e}{2 \times \pi \times F_5} = \frac{\qquad}{2 \times \pi \times \ldots\ldots} \times 10^3 = \ldots\ldots\ldots \text{mH}$$

$$C_7 = \frac{L_e}{R_e^{\ 2}} = \frac{\qquad}{(\ldots\ldots\ldots)^2} \times 10^3 = \ldots\ldots\ldots \mu\text{F}$$

$$R_4 = R_e \quad @5\text{watt} = \ldots\ldots\ldots\Omega$$

Crossover Network:

Crossover point: F_{lo} =..…….……Hz.

L_4 =…..……….mH

C_4 = …………….μF

Frequency factor $\omega_{lo} = 2 \times \pi \times \sqrt[4]{3} \times F_{lo} = 4.77 \times \ldots\ldots\ldots = \ldots\ldots\ldots$

$$\chi = \frac{\sqrt{2}}{2} = 0.707$$

$$C_4 = \frac{\chi}{R_e \times \omega_{lo}} = \frac{0.707}{\ldots\ldots \times \ldots\ldots} \times 10^6 = \ldots\ldots\ldots \mu\text{F}$$

$$\lambda = \sqrt{2} = 1.414$$

$$L_4 = \frac{\lambda \times R_e}{\omega_{lo}} = \frac{1.414 \times \qquad}{\ldots\ldots\ldots} \times 10^3 = \ldots\ldots\ldots \text{mH}$$

Appendix A

TYPE : …………....….......	**P/N** : ...………….......………...	**DATE** : …………………....
	LEFT HAND	**RIGHT HAND**
Tweeter parameters : Crossover point: ……............Hz. R_e F_s Z_{fs} $Z_{fs} = \frac{V_s}{V_r} \frac{mV}{V}$	....……......... Ohms. ......…........... Hz. ....………..…. Ohms. ____________ = ...………......Ohms.	.... Ohms. .... Hz. .... Ohms. ____________ = ...……….....Ohms.
Zobel Parameters : Calculate: $r_o = \frac{Z_{fs}}{R_e}$ Reference impedance : $R_{ref} = R_e \times \sqrt{r_o}$ Record F_3 and F_4 where R_{ref} is above & below Z_{fs}.	r_o = _______ = ……….. R_{ref} = ……. x $\sqrt{\ldots\ldots}$ = R_{ref} = ……….. Ω F_3 = ……….. Hz. F_4 = ……….. Hz.	r_o = _______ = ………... R_{ref} = ……. x $\sqrt{\ldots\ldots}$ = R_{ref} = ……….. Ω F_3 = ……….. Hz. F_4 = ……….. Hz.
Check F_s : (±1 %) $F_s = \sqrt{F_3 \times F_4}$ Hz	$\sqrt{\ldots\ldots x \ldots\ldots}$ = ……… Hz	$\sqrt{\ldots\ldots x \ldots\ldots}$ = ……......Hz
Calculate L_{ref} = Re x √2 Find L_{ref} above F_s and record F_5.(300-1000 Hz.)	= ……. x √2. = ……… Ω F_5 = …………….. Hz.	= ……. x √2. = ……… Ω F_5 = …………….. Hz.

Appendix A

Tweeter Zobel Calculation Chart - Zobel/Butterworth.

Zobel Network:

R_e = ……………Ω **Fs** = ………..…..Hz. **Zfs** = ………..………Ω

L_e = ………....mH. **Q_{ms}** = …..…………… **Q_{es}** = ………..……….

r_o = ………………….. **C_5** = …..……..…μF **C_6** = ………………μF

R_1 = ……………Ω **R_2** = ……………..Ω **L_5** = ……………….mH

Calculate:

F_3: …………….. **F_4**: …………….. (From Speaker Data chart.)

$$Q_{ms} = \frac{F_s \times \sqrt{r_o}}{(F_3 - F_4)} = \frac{\quad \times \sqrt{\quad}}{} = \ldots\ldots\ldots\ldots$$

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

$$R_{es} = \frac{Q_{ms} \times R_e}{Q_{es}} = \frac{\quad \times \quad}{} = \ldots\ldots\ldots\ldots$$

Check: $R_{es} = Z_{fs} - R_e$ = ………..… - ……....…=…………..…

$$L_{ces} = \frac{R_{es}}{2 \times \pi \times F_s \times Q_{ms}} = \frac{}{} = \ldots\ldots\ldots\ldots$$

$$C_{mes} = \frac{Q_{ms}}{2 \times \pi \times F_s \times R_{es}} = \frac{}{} = \ldots\ldots\ldots\ldots$$

F_5 = …………….Hz (From Speaker Data chart.)

$$\mathbf{L_e} = \frac{R_e}{2 \times \pi \times F_5} = \frac{}{2 \times \pi \times \ldots\ldots} \times 10^3 = \ldots\ldots\ldots\text{mH}$$

$$\mathbf{C_5} = \frac{L_e}{R_e^{\,2}} = \frac{}{(\ldots\ldots)^2} \times 10^3 = \ldots\ldots\ldots\mu\text{F}$$

Appendix A

Tweeter cont.

$\mathbf{L_5} = C_{mes} \text{ x } R_e^2 = \ldots\ldots\ldots\ldots\ldots \text{ x } (\ldots\ldots\ldots\ldots)^2 \text{ x } 10^3 = \ldots\ldots\ldots\ldots\ldots\ldots\text{mH}$

$\mathbf{R_2} = \dfrac{R_e^{\,2}}{R_{es}} = \dfrac{(\qquad)^2}{} = \ldots\ldots\ldots\ldots\ldots\ldots\Omega$

$\mathbf{C_6} = \dfrac{L_{ces}}{R_e^2} = \dfrac{}{(\ldots\ldots\ldots)^2} \text{ x } 10^6 = \ldots\ldots\ldots\ldots\ldots\ldots\mu\text{F}$

$\mathbf{R_1} = R_e = \ldots\ldots\ldots\ldots\ldots\ldots\Omega$

Crossover Network:

Crossover point: $F_{hi} = \ldots\ldots\ldots\ldots\text{Hz.}$

$\mathbf{L_1} = \ldots\ldots\ldots\ldots\text{mH}$	$\mathbf{C_1} = \ldots\ldots\ldots\ldots\mu\text{F}$

Frequency factor $\omega_{hi} = \dfrac{2 \text{ x } \pi \text{ x } F_{lo}}{\sqrt[4]{3}} = 8.27 \text{ x } \ldots\ldots\ldots = \ldots\ldots\ldots\ldots\ldots\ldots$

$\chi = \dfrac{\sqrt{2}}{2} = 0.707$

$\mathbf{C_1} = \dfrac{\chi}{R_e \text{ x } \omega_{hi}} = \dfrac{0.707}{\ldots\ldots \text{ x } \ldots\ldots} \text{ x } 10^6 = \ldots\ldots\ldots\ldots\ldots\mu\text{F}$

$\lambda = \sqrt{2} = 1.414$

$\mathbf{L_1} = \dfrac{\lambda \text{ x } R_e}{\omega_{hi}} = \dfrac{1.414 \text{ x }}{\ldots\ldots\ldots} \text{ x } 10^3 = \ldots\ldots\ldots\ldots\ldots\text{mH}$

Crossover Parts List.

\+ = series connection. * = parallel connection.

crossover point = ……….……..…Hz.

Tweeter:

C1 = …..…..….μF = ……..….@……….v ………….@……….v

C5 = ………...μF = ……...…@……..…v ………….@……..…...v

C6 = ……….μF = ……..…@………..v …………@…..……v

R1 = ……...…..Ω = …..……. ………….

R2 = ………..Ω = …..……. …………

L1 = ………..mH

L5 = ………..…mH

Woofer:

C4 = ……...….μF = ……..…@……......v ………..@……..…v

C9 = ……..….μF = ……..…@……..…v ……....…@.……....v

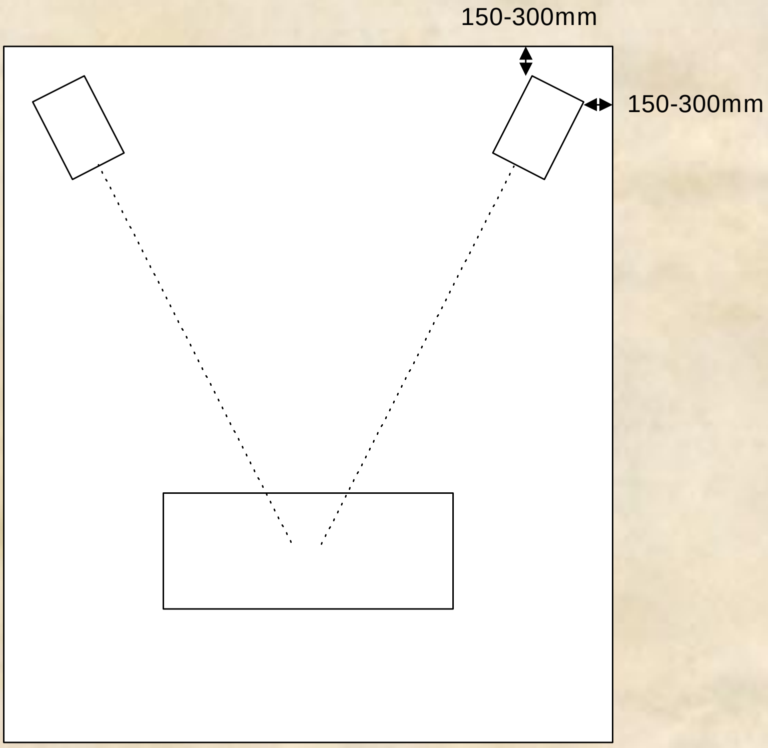
L4 = ……..…mH

R5 = ………....Ω = ……...… ……...…

Note: Use higher voltage caps on parallel connection.

Crossover Parts List.

Speaker placement



Place speakers approximately 150mm to 300mm from the corner walls of your room angled in the direction of your listening position if possible.

Fig 10

Typical driver and tweeter

Soft Dome tweeter

6.5 inch Fibre glass woofer with rubber surround

Fig 11

The Ultimate Loudspeaker Design Revision History

Rev1.0

Added photos of speakers and added Speaker placement diagram.

Rev1.1

Fixed Lpad formula in spreadsheet at cell D14 to read: =D12/B21.
Tidied some drawings.

Rev1.12

Fixed spelling mistake at cell D8 ‘comment’ in spreadsheet .

Rev1.13

Added Appendix A
Updated 2-way schematic – Lpad.

Rev1.14

Added chapter on the speaker measurements.
Removed duplicate words F_{lo} and F_{hi} from crossover calculation charts.

Rev1.15
Fixed schematic component numbering. Fixed component numbering in calculation charts.

Rev1.16

Update to spreadsheet.

Rev1.17

Update to spreadsheet and Qts formulas.