The Lost Art of Loudspeaker Design

S.S.T

Bringing you music at the speed of sound.

A design and construction manual

Mike MacLeod

The Lost Art of Loudspeaker Design.

First edition
P1996.

This Edition 2012.

EISBN : 3FFAC41B-258F-49FF-AF2B-0E193C210CC0

Printed and published by Mike MacLeod,
Benoni.
South Africa.

cammhifi@gmail.com

Other books by the author:

Technical:

Constructors Mate
Map Reading and Navigation for Everyone
The Ultimate Loudspeaker Design

Novels:

Ride The Restless Wind
A Fools Gold

Contents

Contents

Contents

List of figures

List of figures

List of tables

Forward

Why build?

What is High Fidelity? It is the ability to re-create the sound that the recording engineer spent half the night trying to perfect and is ***not*** a 5 in 1 surround sound movie theater system with the bass cranked to maximum. A high fidelity system must be able to re-create each instrument as accurately as possible almost to the point of sounding like the original and one should be able to pinpoint where each instrument is in the overall sound stage.

I was quite happy with the hi-fi that I owned, a B&O 7000 with a pair of P45 speakers that were widely regarded as the best around. There weren't many speakers around to beat them, so why change? Actually my brother Mark was the catalyst, as he decided to build one of those kit amplifiers, a 250-watt job and couldn't find a decent set of speakers to go with it. After auditioning an umpteenth pair, he turned to me and said:

" Let's build our own".
"Not so easy" said I, "Where do we start"?
"No problem" he says, "We go and buy some speakers and chipboard and voilá...."!

This little statement set me on a course that at times seemed impossible to complete. Problems ranging from there being no information available, to realising that the so-called "experts" didn't know what they were talking about either. We purchased a set of woofers and wood and proceeded to build a pair of loudspeakers, just like the boffins said. Well what a disaster, so I decided then and there to start at the beginning and learn as much as I could.

This book then, is a culmination of all the experiments and development that was to take place over the next three years. I make no great claims to be better than anyone else, or to have developed any new techniques (except for one or two), but rather to have applied the knowledge gained during the late fifties and early sixties, especially that of James F. Novak, that has somehow been ignored. It's no secret that the valve amps of the fifties are still superior to anything going at the moment. Needless to say, I eventually mothballed the B&O and built my own system that is far better. I based my system on the Moscode amplifier by Jeff Macauley – it's simply the best.

I firmly believe that the art of loudspeaker design has passed from the engineer to the accountant, who is intent on the bottom line only - the dollar. It is a mass market where quantity rules not quality.

So, if you are one of those people seeking the ultimate sound and who would be proud to say, "I built 'em", read on. If on the other hand you want to learn about loudspeakers or just want to tweak your existing set, then this is an excellent reference to have.

Mike MacLeod.
1996.

Chapter 1.

In the beginning……

I love live music and go to a lot of music festivals. Nothing beats that live vibe and it is always disappointing going home and listening to the ol' hi-fi afterwards. So when I sat down to design my own speakers, the first goal on my list was that the sound had to be as true to live sound as possible. There is nothing worse than symbols or drums sounding as though they were locked away in a cupboard. If someone clanged a symbol next to you, your ears would drop off, or when a bass drum is hit you feel the air vibrate and that is what I wanted! Secondly, the boxes or **bins** as some would call them, had to be reasonably sized. In other words they weren't to take up half of the lounge!

I've always been fascinated by the pyramids and their so-called "mysterious powers". While messing around on a notepad one day, I found a unique ratio to them, which allowed me to find a way of dimensioning speaker boxes so that odd harmonics would not colour the sound and which allows good bass response from reasonably small speaker cabinets. I call this the **GOLDEN PYRAMIDAL RATIO**, or the 'GP' ratio for short. Start off by drawing a horizontal line on a pad, say about 80 mm long. Take a drawing compass centred on this line and using a radius of about 30mm draw a circle. Now draw a line perpendicular to the first through the centre point till it bisects the circle. See figure 1. Label the four points on the circle ABCD starting from the l\h side or 9 'o clock position. Draw two lines from the top of the vertical line at point B down either side to A and C. You should now have a pyramid in the upper half of the circle. Mirror the pyramid in the bottom half as you did in the upper half. Take the compass again and keeping the original dimension of the circle (*do not disturb this setting at all*), draw an arc on side AB using point B as the centre and label this as E. Do the same on side CD on the lower pyramid using point C as the centre and label as F. Join the two arcs EF with a line which is parallel to BC. Rotate the page 45 degrees and you will see your speaker box. If you now divide the height BC by the width EB you get the figure of 1.4142. This is your "GP" ratio. Notice how the line EF that you have just drawn bisects the horizontal line AC, label this point as G. Using the compass centred at F, you will note that an arc cuts point G exactly, *if you haven't disturbed the original setting of the compass, that is*. Using point C as the centre, draw an arc on BC and label as H. Draw a line between GH and you now have a narrow rectangular box in the upper half of your speaker.

1.

This is where the tweeter and midrange speakers are housed. The lower half of the speaker cabinet is perfectly square and is where the woofer fits. See the perfect 3d view of the speaker below:

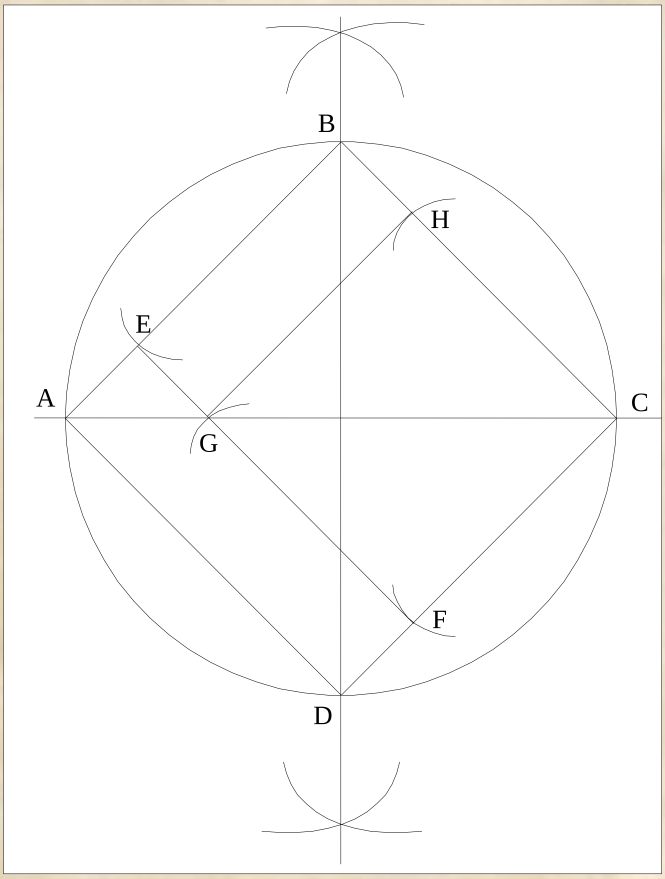


Fig. 1

This then is how the correct dimensioning is obtained. The "GP" ratio can be expressed mathematically as:

$$\text{GP ratio} = \sqrt{2} = 1.4142$$

The drawing we have made is my logo.

1.

Loudspeaker types.

Let's have a look at the types of speaker and their construction. The main speaker is the **woofer** or bass speaker, some people call them drivers, but that's up to you. Woofers are all basically the same, the main difference being the material used to join the paper cone to the metal frame and is called the surround. There are four materials used, namely: paper (older types), cloth (including reinforced), foam and rubber, the first two are used mainly by musicians. The foam type is used in domestic hi-fi systems, as it has a smoother response and gives good bass reproduction. A newer type of speaker has a cone made from polypropylene, but I prefer the paper cone for it's all round performance as the polypropylene ones are too stiff and are more suited to car sound systems where they can handle sun and moisture. The thing to look out for when buying speakers, is that they must look well constructed and by that I mean check the workmanship. Don't go for ones with tiny magnets or shiny chrome centre caps. Usually your budget is the restricting factor here. Expensive woofers might have cast aluminium frames as opposed to pressed steel or nice spring loaded terminals, gold plated to boot. But generally all speakers are the same, it's how you use them that counts. The woofer is designed to reproduce low frequencies in the 50 to 500 hertz range with power handling of between 50 to 300 watts rms.

The next speaker we encounter is the **midrange** unit and as its name suggests, it handles frequencies of 500 to 5000 Hz. There are also one or two types but generally they are similar to woofers but only smaller. The principal feature is that they are mounted in a sealed tube so that the woofer's sound waves cannot disturb their cones, when they are mounted in the same box. There is one type of unit that employs a metal dome, but they tend to be expensive and sometimes need notch filters to tame their peaks, that is, they tend to sound harsh at certain frequencies. Midrange drivers handle the bulk of the music spectrum but not the bulk of the power. This is handled by the woofer, so the power rating doesn't have to be that high. In later years a technique of using a fine magnetite powder **(Fe^3O^4)** suspended in a special low viscosity oil, designed for jet engine lubrication and being able to withstand high temperatures, was injected into the gap between the coil and magnet pole. This helped transfer heat away from the coil, allowing higher power ratings. A spin off of this was the fact that it enabled the coil to align perfectly with the magnet pole piece during assembly. What happens is that the particles get suspended in the magnetic field and align themselves evenly around the coil acting like ball bearings. This is known as **Ferro fluid cooling**.

Tweeters are the last of our speakers and are much smaller, coming in a variety of shapes and sizes. They should also be fully enclosed at the rear like the midrange unit. They also employ Ferro-fluid cooling and handle the least power as their frequency range is much higher, about 4500 to 20000 Hz. Tweeters differ a lot between manufacturers but generally consist of soft dome or hard domes, again, I prefer the soft dome types. Also remember that tweeters can only handle between 5 and 15 watts max, so be wary of any that are rated higher. Usually manufacturers will specify a higher rating only with the appropriate crossover. Another type of tweeter is the piezo type, which is not suitable for hi-fi use.

Load impedance.

Loudspeaker impedance, denoted Z, is the **load impedance** in ohms of the speaker when driven by a signal and varies with a change in frequency. Manufacturers rate their speakers as 4 or 8 ohms, but if you measure the voice coil d.c. resistance with a multimeter you'll find it is actually lower.

Why then, the two types? When car radios became popular, the technology at the time restricted the amplifier output to only a few watts from the vehicles 12-volt system. Also 8 ohm speakers became standard as valve amplifiers were being replaced by transistor types. It was the rating of these transistors that determined the output power, as their voltage ratings were rather low. A 12v supply limited the amplifier driving an 8Ω load to about 2w rms. This is due to the output transistor's peak to peak voltage swing being 2 to 3 volts less than the supply. Halving the speaker load to 4Ω gave about 5w rms and was the easiest way to increase power, but at increased current draw. Today modern car amplifiers are powered by switched mode power supplies to give higher powers but 4Ω speakers remain the car choice, hence the very heavy duty supply cables etc.

For hi-fi use we stick to 8Ω speakers and I wouldn’t recommend going lower as one doesn't know what type of **output stage** is employed in your amplifier. Using a 4Ω load might lower the impedance too much, resulting in high current draw blowing the output transistors and don't forget that the power supply might not be suitably rated either. Also do not connect 4 speakers to your amplifier for the very same reason. Don't mix types either, e.g. an 8Ω woofer with a 4Ω tweeter or midrange, because the overall impedance of the crossover will be too low as well as a mismatch between the speaker's sensitivities.

Some amplifiers have the facility for connecting an extra set of loudspeakers for use in say another room, with a switch on the front panel to switch them in or out. What they neglect to tell you is that only one pair of speakers may operate at a time. My first B&O was like this and not knowing any different at the time, I connected 4 speakers for a pseudo quad system but blew the output trannies in no time flat. They could have avoided this by inter-connecting the two switches so that only one set of speakers could be on at a time. (I still have the manual and still can't see any warnings to this effect). ***So be warned.***

Choosing speaker drivers.

So then, how does one choose the right speaker for your system? First off, the system that we are going to build uses 8ohm, 12 inch woofers which are relatively cheap for their size. Bass frequencies are very low and using the sea as an analogy you know that the bigger a wave is the more powerful it is and conversely small waves are no bother at all. So it’s no use trying to use a small speaker to push out “ big” waves. Here it is air that the diaphragm is pushing so the bigger the better. I don’t want to get too involved in theory and heavy acoustical science, but it is worth discussing the power factor in relation to cone excursion. Generally one doesn’t know what parameters are used by manufacturers to rate their speakers and therefore the comparisons can vary. As a rule of thumb, if the word **RMS** (root mean square) doesn’t follow after the watt figure, then it is safe to assume that it is peak power and should be divided by at least two to get an approximate RMS value. The RMS figure is more realistic than peak power, but for it to be really meaningful, the manufacturer should state at what frequency it was obtained and is usually a sine wave at 1000Hz. The term RMS, basically, is the point where A.C. (sinewave) power has the same heating effect as the equivalent D.C. power with a resistive load and is .707 of the peak ac voltage**. Peak music power** or max power is totally meaningless as different styles of music and different instruments generate different frequencies that will give different power peaks. Now for a speaker to operate without distorting or loosing efficiency, its **cone excursion**, that is, its peak-to-peak piston (cone) travel must not be exceeded, 13mm being the maximum allowable limit i.e. 6.5mm forward to 6.5mm rearward. The following table lists three sizes with their excursions for 1 acoustical watt (the mechanical action to produce one watt of power) at 50 Hz:

RATED DIAMETER	ACTUAL DIAMETER	PEAK-TO-PEAK EXCURSION TO PRODUCE 1a/W @ 50 HZ.	ACOUSTICAL POWER OUTPUT FOR MAX. CONE EXCURSION.
200 mm - 8 inch	172 mm	45.72 mm	0.06 w
304 mm - 12 inch	266 mm	20.32 mm	0.40 w
380 mm - 15 inch	336 mm	13.5 mm	0.95 w

From this table, it can be seen that all of the driver's cone excursions exceed this limit (the 15 inch just misses the limit).

Various factors govern a loudspeaker's performance and are summarized as follows:

- If the cone area is doubled, the excursion is halved.
- If the frequency is halved, the cone excursion increases by a factor of 4.
- If the cone excursion is halved, the acoustical power is halved.
- If the cone area is doubled and the cone excursion remains the same, the acoustical power is increased by a factor of four.

A full orchestra can reach close on 120 dB_{spl} (**decibels sound pressure level**) and if you want to produce this dynamic range in your listening room, then this would be the level to aim for. It takes 0.4 of an **acoustical watt** to produce 100 dB_{spl} at 2.5 meters with a system that is 100% efficient. Now the most efficient speaker system ever made approached 50% efficiency (a massive horn speaker taking up three rooms) and most systems are lucky to reach 1% or 2%, with a lot of commercial ones only reaching 0.1% to 0.2%. So, a system that is 10% efficient would require 400 watts and one that is 1% efficient 4000 watts. Our commercial type, at 0.1%, would need some 40000 watts! One can use the following parameters to determine the number of drivers required producing at least one acoustical watt and not exceeding the cone excursion limit.

1.

The following refers:

Size of driver	Number of drivers required
200mm. (8 inch)	5
304mm.(12 inch)	3
380mm.(15 inch)	2

If one sat closer to the speakers than 2.5m, say 1m, then a 6dB_{spl} increase occurs. A speakers **sensitivity** (efficiency) is quoted as so many dB's at a distance of 1m for 1 watt input. For example you might see the following: sensitivity = 89 dB_{spl} at 1m/1w. Now for every 3dB_{spl} increase required, the amplifiers output power must double. So for our speaker to give out 92 dB_{spl} (89 + 3) we need an amplifier of 2 watts and for 95 dB_{spl} (89 + 3 + 3), 4 watts. Therefore to get to 120 dB_{spl} we need 1024 watts! So when looking at woofers go for the highest sensitivity. At this point I must mention that three-way crossover networks give a 2 dB_{spl} gain in their mid band section, so aim to buy a midrange speaker rated about 2 dB_{spl} lower than the other two. The woofer and tweeter can have the same sensitivity rating. The max power rating is not that critical, as long as you try and match the speaker power to the amplifier, but if you can't don't despair, a 100 w RMS speaker on a 250w amp is okay. The speaker will distort long before you exceed its rated capacity. What can damage a loudspeaker though, is trying to drive an amplifier to its maximum power, which is usually the case with low powered amps. The amplifier starts to clip, resulting in massive bursts of distorted power blowing the speaker coil windings. It's better having a high powered amp than an under powered one. The following formula will indicate your chosen speaker's **maximum output**:

$$\boxed{\text{Output } dB_{spl} = 10\text{Log}(p) + s}$$

p = continuous RMS sine wave power rating. **s = quoted sensitivity.**

For example a speaker may be rated as 100 w RMS with a sensitivity of 92 dB_{spl} at 1w/1m, then: Maximum dB_{spl} = 10Log(100) + 92 = 112 dB_{spl}. In other words this is the maximum level you can expect from this speaker. You might have heard of the term **dynamic headroom** or just plain headroom. In music it is the difference in spl between the softest note and the loudest note. Used in relation to sound systems, it is the difference between the speaker's max spl to that of the ambient noise level. The quietest sound which can be heard in a given environment depends entirely upon the background noise level of that environment. Unfortunately, most people live in close proximity to traffic, neighbours with television sets, dogs, and noisy children, and these things, together with the normal background sounds of the home, combine to give an ambient noise level of about 50dB. The minimum sound level which can be distinguished clearly above this background level is therefore 53dB. The dynamic range of orchestral music can be as much as 70dB, therefore in order to be able to hear the pianissimo as well as the fortissimo passages, a peak level of 123dB is required. So the total dynamic range of a symphony orchestra cannot be heard in comfort with your loudspeaker of 112 dB_{spl} max. That is why it is better to listen to music at night as the ambient sound level is much lower and therefore we state that we have more headroom or greater headroom.

The **crossover network** splits the power approximately in the ratio of 60-25-15 percent between the three speakers and will be your guide to buying your drivers. For an amplifier of 100 watts output, the woofer would get 60 watts, the midrange 25 watts and the tweeter 15 watts. I use a Philips midrange and tweeter rated at 40 watts and 15 watts respectively and my amplifier is rated at 150 watts and to date have never had any problems (I often run it full bore when doing demo's). A word of warning though, this kind of level can lead to you going deaf very quickly and what will the neighbours say?

<u>Summary</u>

1. Woofers with foam or rubber surrounds are best.
2. Mid's and tweeters must be fully enclosed at the rear.
3. Choose midrange speakers with a sensitivity of $2dB_{spl}$ lower than the other two speakers.
4. Use speakers rated at 8 ohms for hi-fi use.
5. Halve any power figures quoted on speakers that do not have the word RMS printed on them or in the specifications.
6. Remember that low power amplifiers blow tweeters and high power ones rattle woofers.
7. The higher the sensitivity the greater the dynamic range.
8. Power in three way crossover networks is split 60/25/15.

Chapter 2.

How low can you go?

Remember that the lower the frequency, the higher it's power, which also means that it requires a lot of power to produce. It also requires a certain distance to propagate, that is, to develop fully. A typical sound or note consists of waves and the distance from the crest of one wave to the crest of the next is called its wavelength and is measured in meters. It follows then that a room's dimensions will affect this **wavelength** and therefore we can say that the longest dimension determines the lowest frequency.

$$F_L = \frac{170}{d}$$

F_L = lowest frequency **d = longest room dimension**

A room 7m long then limits the response of your system to $\frac{170}{7}$ = 24 HZ.

If you intend building a sound room, don't forget to take this into account. To determine the actual **room dimensions** we use the "GP" ratio. Using the example above, we see that if we aim for a lowest frequency of 24 HZ, then the length of the room should be 7m. Now if we divide this by the "GP" ratio, 1.4142, we get the room's width which is 4.94m. Dividing this figure again by 1.4142, we get the ceiling height of 3.5m. If you're stuck with an existing room then all you can do is work out its response, that is, its lowest frequency. Also most modern homes have ceilings at the minimum height, which is approximately 2.6m. This then would, if you work backwards, give a lowest frequency of 32 HZ. Another factor that is going to affect this frequency, is the speaker's resonant frequency, which will be discussed shortly.

Speaker Cabinets.

As with our room, a speaker cabinet too has an ideal size. The cabinet can be too large resulting in **boominess**, that is, it sounds hollow and not as distinct or tight as it should. It can also be too small resulting in very poor bass response. The box we are going to build is called a **ducted phase**

inverter, which is a cabinet with a port inserted into it. This allows the air at the back of the woofer's cone to reinforce the sound coming from the front of the cone. You would think that as the cone moves outwards, it would suck air into the box, but due to the **duct's compliance** and other factors, the air is inverted and exits the duct in phase with that at the front of the cone. To aid in working out the size of the cabinet, I have drawn up charts and all you do is fill in the basic parameters and follow the sequence and am therefore not going to go into any great detail, except to explain by giving examples.

<u>What types of material?</u>

The wood used in the manufacture of speaker cabinets is called M.D.F **chipboard** - medium density fibre, (not the low density "industrial grade" that is usually sold), which was specifically designed for loudspeaker manufacture. It comes either plain or veneered, that is, it has a thin layer of wood bonded to it, giving it the appearance of natural wood like oak, kiaat, cherry, pine etc. The minimum thickness to use is 16mm and no real improvement in sound warrants going any thicker. A modern trend is to use Supawood, a hardboard type of material, also coming in various styles. The parts of our cabinet are labelled as follows: The sides, top and bottom, naturally, the sides, top and bottom. The front and rear panels are referred to as **baffles**, the front actually consisting of two baffles, namely the woofer baffle and the mid / tweeter baffle.

<u>Phase distortion.</u>

It has long since been known that the incorrect positioning of the drivers (speakers) in relation to each other, that is, from a fixed reference or datum point in front of the cabinet to their voice coils, causes **phase distortion**. This happens because the high frequencies arrive at your ear slightly ahead of the low ones, due to this axial displacement, which causes them to be out of synchronisation with each other, as compared to that of the original signal. In severe cases it produces an echo and it has been found that the ear can detect differences as short as 3 milliseconds, especially on instruments such as castanets. Ever been to a racetrack that has speakers all around the ground and when the commentators talk, they sound like they're inside an echo chamber? **Bang and Olufsen** of Denmark were the leaders in investigating this phenomenon and wrote several papers on the subject. That's why headphones always sound so good, there is no phase distortion. With a bit of lateral thinking and design, I was able to come up with an improvement on this, with amazing results, see **figure 2** below. Notice that the tweeter\midrange is recessed.

Fig 2

Dimensions.

It is important to realize that all the **dimensions** that we are going to use in determining our cabinet size, refers to inside measurements, that is, they don’t take into account the thickness of the timber, which allows you to decide what thickness you want. As you progress through the chart, so you will get to add this figure in and the materials list will then have this taken into account. Another factor to take into account is that the **cabinet corners** are cut at 45 degrees and you must add twice the wood thickness to the internal measurements when calculating final panel height and widths, but is allowed for in the charts. The problem, though, is in cutting the 45-degree corners and if you’re having this done by your local timber merchant, point out that the dimensions refer to the final width, that is,

2.

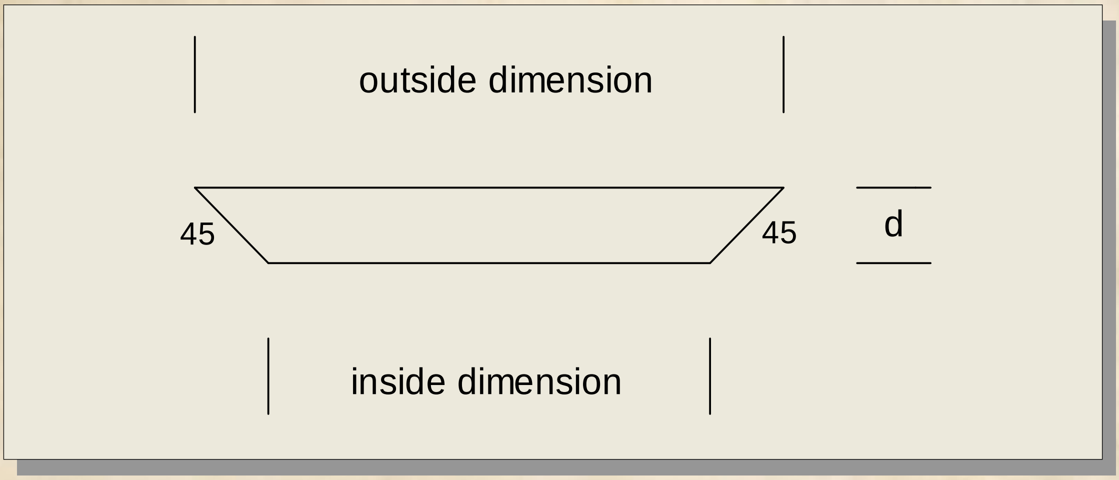


Fig. 3

Outside dimension = Inside dimension + 2d

d = thickness of timber

after the 45-degree cuts. See figure 3 , otherwise you might end up with your panels short by the amount of the thickness of one plank. ***Remember, measure twice, cut once***. Ask me, I know! If you elect to design your cabinet differently by using butt joints or any other method, then remember to work out whether the wood you are about to cut is an inside piece or an outside piece. Outside pieces have twice the wood thickness added to them. Another point to look out for, when cutting the top, sides and bottom, is that the grain of the wood is running along the length of the panel. Cutting the angles to 46 degrees allows a better fit, as sometimes the glue causes a gap in the joints.

Ducts, tubes or ports.

The tubes for the **ports** can be made out of cardboard or ideally 50mm pvc drainpipe. When calculating the length of the port remember it is measured to the outer face of the front baffle, so if you elect not to have the tube flush with the baffle front face, to take this into account. I fit the tube so that it is flush with the outside face and then router a radius on its inner diameter, which looks neater.

Minimum tools required.

What **tools** does one need then? You can get by on the minimum of the following:

A drilling machine.
Jigsaw.
Set of hole saws for a drilling machine.
Set of screwdrivers.
Rubber sanding block and 220 wet&dry paper.
Soldering iron.

Don't despair if you don't have a whole workshop full of tools and special equipment. I find it easier going to one of the big timber merchants or DIY shops and asking them to cut the wood for me and if you have a cutting layout it goes pretty quickly. See figure 4, for a **cutting layout** that includes pieces for another project. You might even find a small cabinetmaker or cupboard factory to cut the chipboard for you. Let your fingers do the walking........

Cutting plan.

To make a cutting plan, draw the outline of the board (chipboard comes in the standard size of 2750mm x 1830mm, but check with the timber merchant), on a piece of graph paper. Then draw in the pieces in pencil, so that you have the least amount of wastage. You might have to shuffle them around until they fit exactly. After a while you'll get the hang of it and this method is handy for any project requiring timber cut to size from large boards. Just make sure that the pieces are laid out in such a way that the number of cuts is kept to a minimum. The first lengthways cut might have two sides and a top in it and the second another two sides and bottom. Remember you are making two speaker cabinets so will be cutting double the amount of wood. Once you've done the rip cuts, that is, the lengthways cuts, you do the crosscuts. The left over pieces might be useful for other projects, like perhaps a surround sound add on, which

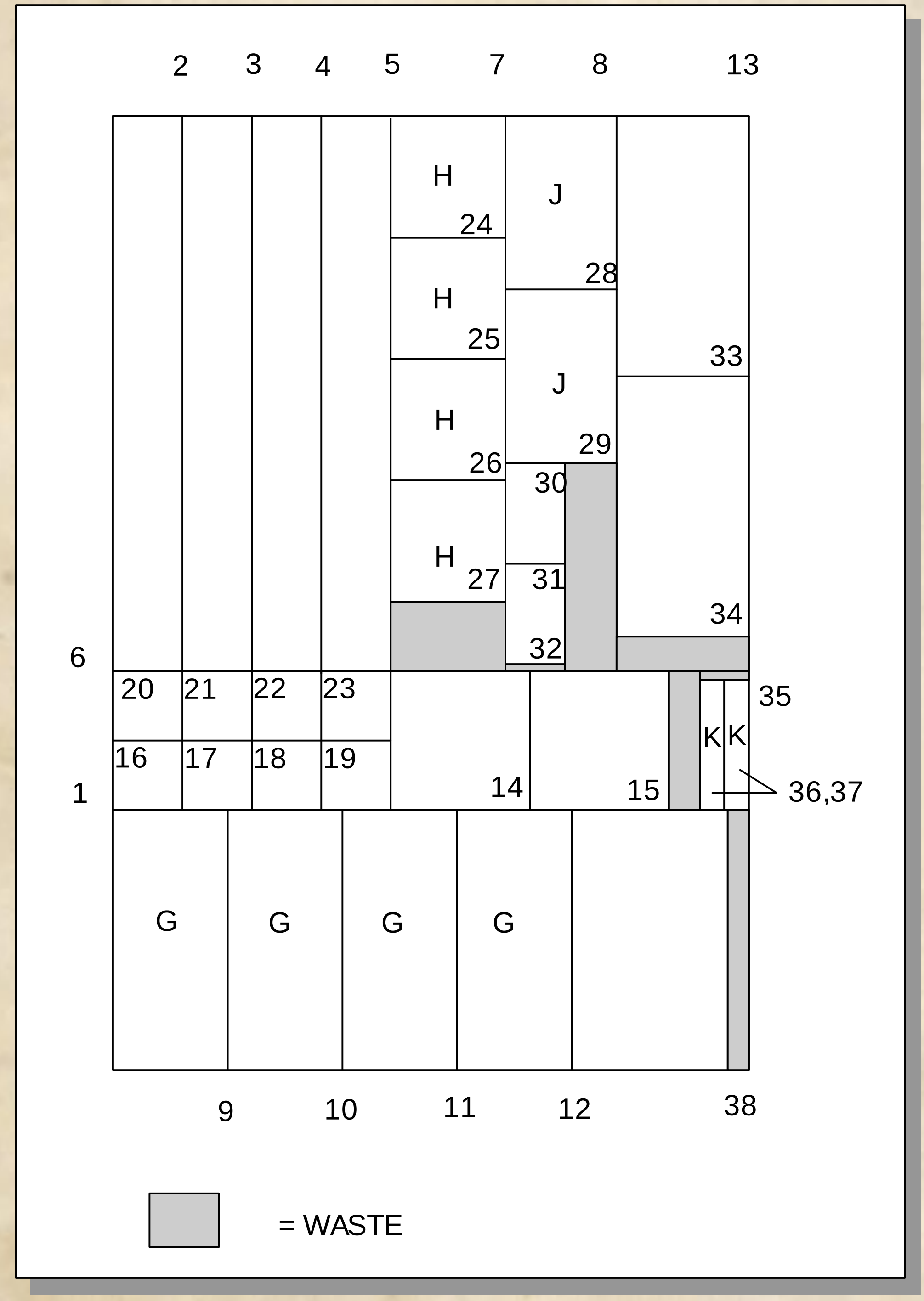

2
3
4
5
7
8
13
H
24
J
28
H
25
33
J
H
29
26
30
H
27
31
34
6
32
20
21
22
23
35
K
K
16
17
18
19
1
14
15
36,37
G
G
G
G
9
10
11
12
38
= WASTE

Fig. 4

2.

is covered in my book "Home Theatre. A design and construction manual". I also label my cutting chart with the sequence of cuts, which allows me to work out the best method of cutting without having to change the saw set-up too much. Another important point to take into account when working out the layout and final sizes, is to remember to add in the **saw kerf**, that is, the width or the amount that the blade cuts and on my saw is about 4mm. Or use a sheet cutting software program.

<u>Now that you've purchased your speakers!</u>

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.

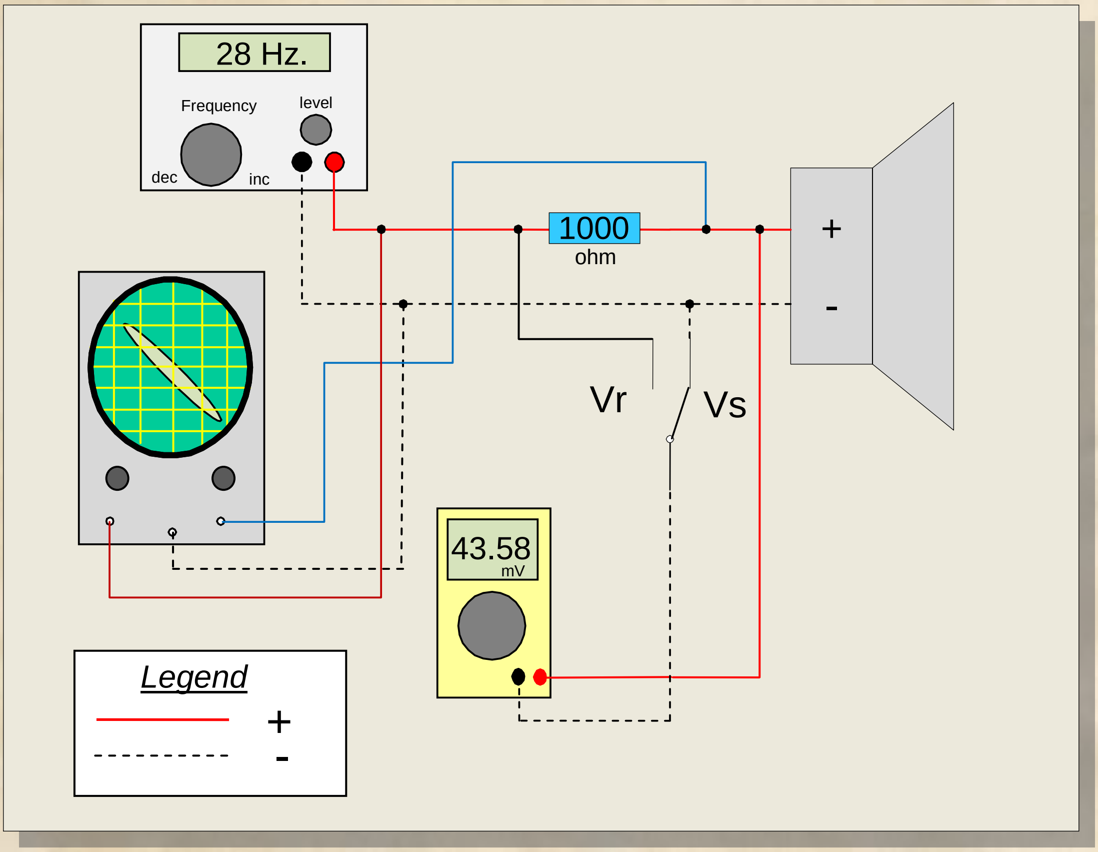


Fig. 5

The frequency where this maximum resonance takes place is known as the speaker's **resonant frequency**. A second phenomenon that occurs, is the change in **impedance** as the frequency changes and this is where people make the mistake when determining the values of crossover networks. They use the manufacturers quoted figure of either 4 ohm or 8 ohms and are quite incorrect. To do all your measurements, you will need a voltmeter, audio generator with variable voltage output and a frequency meter. Connect your speaker up as per figure 5. You could make up a box with phono sockets and the switch fitted, then wire in the 1000-ohm resistor directly to the tabs, to make life easier.

Test setup.

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. I prefer a DMM here (**digital multimeter**). 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 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

2.

the frequency, watching the multimeter. It will start increasing to a maximum and then start to drop. With the reading at its highest, 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. This is known as the resonant frequency, **F_s**. Now look at the "Impedance data chart", **figure 6** below and set each frequency, making sure that V_R is 1 Volt and record the impedance reading on the 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.

Impedance data chart

FREQUENCY HZ.	**V_S mVolts.**	**V_R Volts.**	**IMPEDANCE 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			
28	***42.01***	***0.964***	***43.58***

Fig. 6

2.

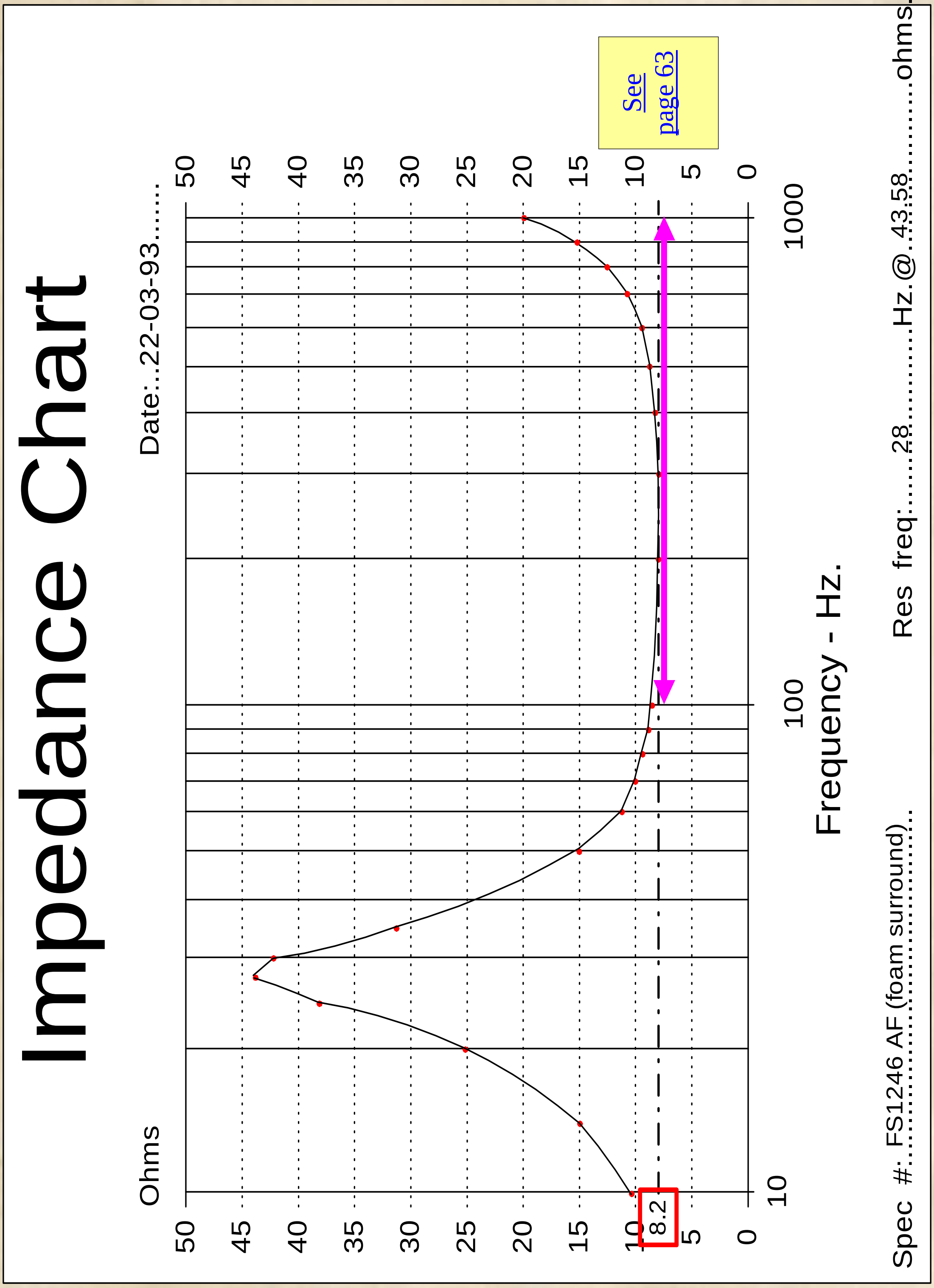

Impedance Chart
Date:...22-03-93.......
Ohms
50
45
40
35
30
25
20
15
10
5
0
8.2
10
100
1000
Frequency - Hz.
See page 63
Spec #:..FS1246 AF (foam surround)..........
Res freq:........28.............Hz.@..43.58...........ohms.

Fig. 7

2.

When you have finished tabulating all the data, you can plot your impedance curve on the "Impedance Curve chart". See figure 7. It is interesting to note that the speaker is at its most efficient at resonance, yet the amplifier is giving the least power due to the high impedance, hence the saying " The wattage goes as the impedance grows". 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.

Measurements galore.

If you now look at figure 8, you will see that it makes provision for working out the **impedance** for the crossover networks, as well as data for tuning the cabinets. The page is divided into two, L/H and R/H, which refers to the left hand and right hand speakers in your system. The second row is used to work out the impedance of the speaker at the desired **crossover points**, usually at 500 HZ and 5000 HZ in three-way systems. You will see each block has place for two calculations and this is for the midrange driver (with sample figures in the R/H speaker column) , which operates between the two frequencies of the crossover points. To avoid confusion, the subscript to Z is left open for you to fill in and allows you to identify the chart quickly. X represents the following subscripts: w = woofer, m = midrange, t = tweeter.
The sample chart refers to our woofer that was tested and tabulated in figure 6. There is also place in the side column to detail at which frequencies the figures were taken.

To measure R_e accurately, set your digital multimeter to its lowest setting and then short your test leads together and note their resistance, about 0.2Ω. Subtract this from your final readings for best accuracy, especially on readings below 10Ω. The following terms are used:

F_s = Speaker resonant frequency.
Q_{ts} = Total Q of the speaker.
R_e = Is the D.C. resistance of the coil measured with a multimeter.
Z_{fs} = Impedance at resonance.
Z_{F3} = Is .707 of the value of Z_{fs}.
F_1 = The frequency above F_s where the impedance equals Z_{f3}.
F_2 = The frequency below F_s where the impedance equals Z_{f3}.

2.

TYPE : …**Akayo**…. **P/N** : …….**FS1246 AF**……… **DATE** : ……**22-3-93**…....

	LEFT HAND	**RIGHT HAND**
Woofer parameters :		
R_e	……**6.8**….. Ohms.	………………… Ohms.
F_s	…..**28.0**…. Hz.	………………… HZ.
Z_{fs}	…..**43.58**... Ohms.	………………… Ohms.
Z_{f3}	…..**30.81**… Ohms.	…………… Ohms.
F_1	…..**36.0**…. Hz.	…………… Hz.
F_2	…..**22.0...** Hz.	…………… Hz.
Q_{ts}	……**0.79**..	……………
$Z_{fs} = \dfrac{V_s}{V_r}\ \dfrac{mV}{V}$	$\dfrac{43.58}{1}$ = Z_{fs} = …**43.58**..Ohms.	$\dfrac{\quad}{\quad}$ = Z_{fs} = ……...Ohms.
Crossover points: F_h = …**500**.......Hz. F_h= F_l = …**4500**..…Hz.	$Z_w = \dfrac{5.6}{0.648}$ = Z_w = ..**8.64**...Ohms.	$Z_m = \dfrac{5.9}{0.762}$ = Z_m = …**7.8**...Ohms.
X = w-woofer F_l= m-midrange t-tweeter	$Z_{\_} = \dfrac{\quad}{\quad}$ = $Z_{\_}$ = ….........Ohms.	$Z_m = \dfrac{7.8}{0.762}$ = Z_m = .**11.18**...Ohms.
Zf3 = 0.707 x Zfs	Z_{f3}=.707 x 43.58 = 30.81 Ω	Z_{f3}=.707 x …… = ……...…Ω
Speaker Q: $ro = \dfrac{Z_{fs}}{R_e}$ $Q_{ts} = \dfrac{F_s}{F_1 - F_2} \times \dfrac{R_e}{Z_{fs}} \times \sqrt{ro}$	$ro = \dfrac{43.58}{6.8} = 6.40$ $Q_{ts} = \dfrac{28}{36-22} \times \dfrac{6.8}{43.58} \times \sqrt{6.40}$ Q_{ts} = ……**0.79**….........	ro = ... = ... Q_{ts} =........ x .... $\sqrt{\ldots}$.......... Q_{ts} = ...
Check $\mathbf{F_s}$: (±1 %) $\mathbf{F_s} = \sqrt{F_1 * F_2}$ Hz	$\sqrt{..36...x...22..}$ = ..**28.14**..Hz	$\sqrt{...........x.........}$ = ……......Hz
Max Output. SPL =10LOG(P) + S P= rms watts. s=sensitivity.dB@1m/1w	=10LOG...100....+...92........ =.........**112**........... 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.)	= ..6.8.. x √2. = .**9.61**.. Ω F_5 = ……**615**….. Hz.	= …… x √2. = ……… Ω F_5 = …………….. Hz.

Z_{f3} = .707 x Zf_s
F_1 and F_2 is the frequency of Z_{f3} above and below F_s – the 3dB points.
L_{ref} is for Zobel impedance equalisers for some woofers whose impedance curve rises sharply above +-600Hz. See Fig 7.

Fig. 8

2.

The resonant frequency, F_s and its impedance $\mathbf{Z_{fs}}$, is taken from the chart in figure 6. Calculate Z_{f3}, which is 43.58 x .707 = 30.81 ohms, this is where the signal power is 3dB down. Set the resonant frequency on the audio generator and then slowly increase it until the DMM reads 30.81 and record this frequency as F_1. Now slowly decrease the frequency below resonance until again you get 30.81 on the DMM and record this as F_2. At the bottom of the chart is a formula for checking F_s using F_1 and F_2 and the result should be within ±1 % of each other.

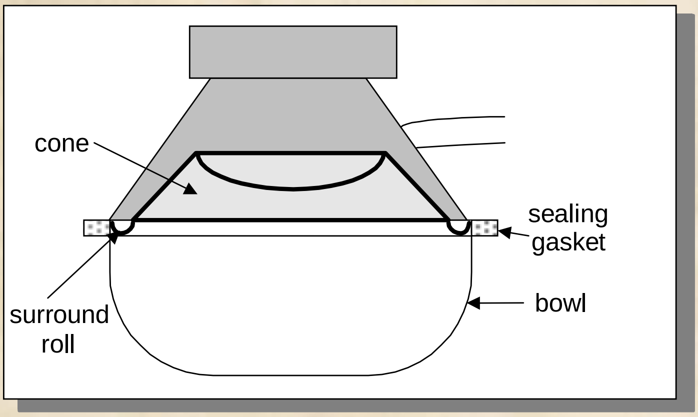
The **Q** of a speaker refers to the magnification of the cone's movement at resonance as compared to that at other frequencies and basically means that a speaker with a high Q is more resonant than one with a low Q. For our purposes, we use it to determine where we're going to tune our cabinet to. If the Q is greater than .38, we tune the cabinet below the resonant frequency and vice a versa if it is less than .38. When choosing a frequency to tune the cabinet to, stay within the limits of F_1 and F_2. You could even tune it to the resonant frequency F_s (as suggested by James F. Novak), if you wish, as there are no hard and fast rules here. Feel free to experiment, it's your ears that are going to be the final judge.

I find it best to write all the key figures and answers down in red, as this helps to pick them out easily. Remember that if you get weird answers, to re-check your calculating, taking special care where you put decimal points!

To level the playing field somewhat and allow easy comparisions between woofers, use the following formula to calculate a **reference efficiency** for the speaker. This does not indicate the efficiency of your system but is rather a relative figure for a particular driver, enabling comparisons between speakers from different manufacturers. Efficiencies range between .1 and 3%.

$$\eta_{eff} = \frac{0.0953 \times (F_s^{\,3} \times V_{as}) \times 10^{-8}}{Q_{es}}$$

$\mathbf{V_{as}}$ is a Thiel\Small parameter in liters. Sometimes it is quoted in cubic feet so multiply it by 28.32 to convert to liters. Q_{es} is the electrical Q of the speaker and is also given with the Thiel\Small parameters. To calculate V_{as} we have to measure the resonant frequency of our speaker in a standard test box, which consists of a sealed box of known volume V_{box}, that has a cut-out on top slightly smaller than the loudspeaker sealing gasket. The speaker is then pressed face down quite firmly over the cut-out and the resonant frequency, F_{box} is measured using the test setup in figure 5. For our purpose it is easier to use a plastic mixing bowl that fits



Tupperware test

just inside the sealing gasket (inner flange) of the speaker and to find it's volume, you fill it with water from a measuring jug and note how many liters it takes. Use the following formula to calculate V_{as} :

$$V_{as} = 1.15 \times \left(\left(\frac{F_{box}}{F_s} \right)^2 - 1 \right) \times V_{box}$$

For example, a speaker with an F_s of 58 Hz, an F_{box} of 67 Hz and the volume of the plastic container V_{box} is 23liters, with a Q_{es} of 0.77, then:

$$V_{as} = 1.15 \times (1.334 - 1) \times 23 = 8.85 \text{ L}$$

Calculate the relative efficiency η_{eff} as follows:

$$\eta_{eff} = \frac{0.953 \times (58^3 \times 8.85) \times 10^{-8}}{0.77} = 3.39 \%$$

See Appendix A for calculating Q_{es}.

Summary.

1. The longest room dimension determines the lowest frequency.
2. The "G.P" ratio is used to calculate room and speaker cabinet dimensions.
3. Use 16-mm MDF chipboard for the cabinet construction.
4. All dimensions for calculating the cabinet volume are inside ones.
5. Do all speaker measurements outside in still air clear of any obstacles.
6. When selecting a frequency to tune the box to, keep within the limits of F_1 and F_2.
7. Calculate a woofer's relative efficiency for easy comparison between makes.

Chapter 3.

Off to work we go.

We use the " Speaker box calculation chart", figure 11, to determine the **volume** and dimensions of our speaker cabinet. First off, we work out the **ideal volume** V_i , that is , the volume of the cabinet without the drivers fitted. Then, because of their physical size and the consequent space they take up, we have to calculate each driver's volume and add it to V_i. My **driver parameters** were as follows :

Driver parameters

	Diameter	Radius - R	Radius - r	Height – H
Woofer	275 mm	137 mm	72 mm	120 mm
Midrange	104 mm	52 mm	-	80 mm
Tweeter	70 mm	35 mm	-	11 mm

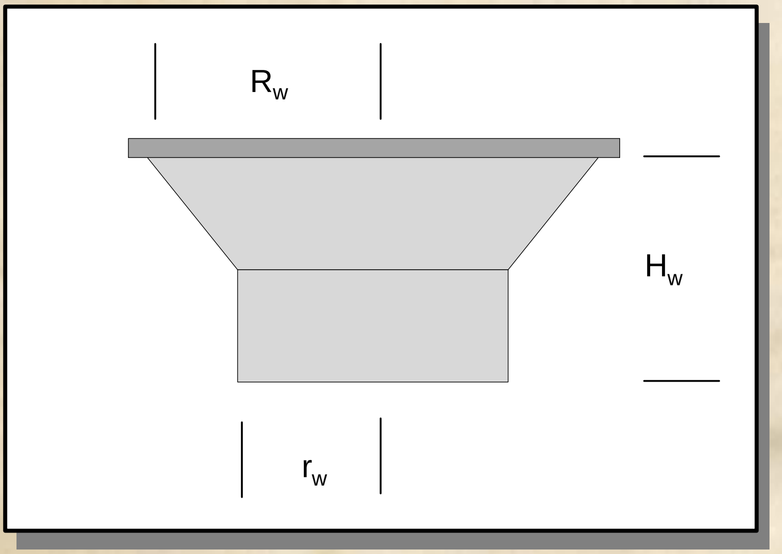


Fig 9

In the formulae, R_w refers to the woofer radius across its inner diameter, that is, the diameter excluding the width of the flange and r_w refers to the radius of the magnet. H_w is the height or distance from the lower mounting face of the speaker, to the rear face of the magnet. See figure 9. R, for the midrange and tweeter, is the radius of the tube or magnet because in most cases they are cylindrical in shape.

Speaker positioning.

To eliminate phase distortion, the midrange and tweeter are mounted in a special **recess**, which also takes up space and therefore has its volume added to V_i. The depth of the woofer's dust cap, that is, the round dome in the centre of the cone, determines the depth of the recess and must be measured, see figure 10. To do this, place a straight edge across the speaker face and measure the depth to the cone and record as W_{cone} on

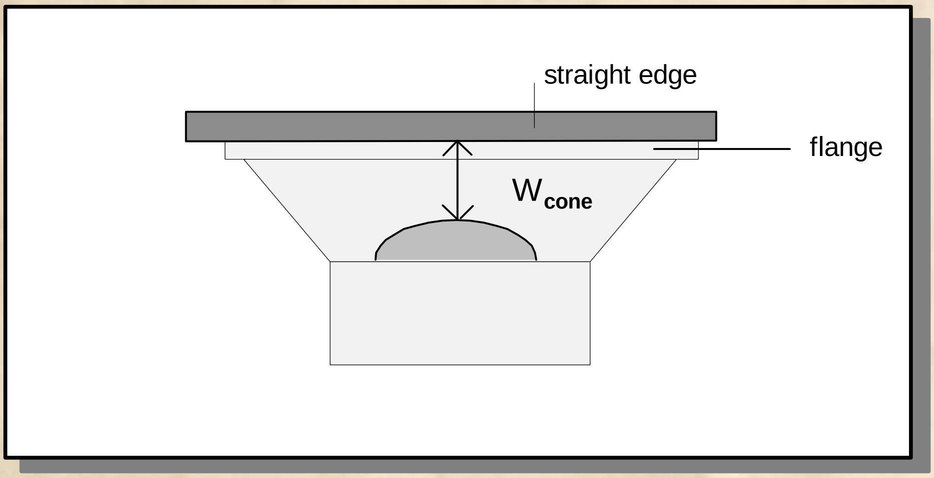


Fig. 10

the chart - (minus the width of the ruler of course). Do the same for the midrange, recording the dimension as M_{cone}. By now you should be getting used to the way various parts or data strings are labelled, usually the first letter identifies the part and the subscript labels it. At this stage don't worry about the tweeter as its size allows it to align with the midrange perfectly when mounted on the baffle. You must now decide whether the drivers are going to be mounted flush with the baffle front face or are they going to stand proud, that is, stand out.

3.

Loudspeaker Dimensions

Woofer	Akayo	Fs1246af
Outside diameter	W_{diam}	305mm.
Woofer radius	R_w	137mm.
Magnet radius	r_w	70mm.
Woofer height	H_w	120mm.
Cone depth	W_{cone}	48mm.
Flange thickness	W_{flange}	10mm.
Flange width	W_{rebate}	10mm.
Cut-out diameter	W_{hole}	285mm.
Mounting screws		M6
Midrange	Philips	AD5062/SQ8
Outside diameter	M_{diam}	122x122mm.(hex)
Tube radius	R_m	52mm.
Tube height	H_m	80mm.
Cone depth	M_{cone}	12mm.
Flange thickness	M_{flange}	11mm.
Flange width	M_{rebate}	9mm.
Cut-out diameter	M_{hole}	104mm.
Mounting screws		M4
Tweeter	Philips	AD11610T8
Outside diameter	T_{diam}	96x96mm.(square)
Magnet radius	R_t	35mm.
Tweeter height	H_t	15mm.
Cone depth	T_{cone}	1mm.
Flange thickness	T_{flange}	3mm.
Flange width	T_{rebate}	13mm.
Cut-out diameter	T_{hole}	70mm.
Mounting screws		M4

3.

If you elect not to recess the woofer and midrange into their baffles, then the flange thickness has to be measured and recorded and was 10 mm for my woofer and 11 mm for the midrange. If, on the other hand, you do recess the drivers, then the dimension "flange" in the formula, is zero.

Cabinet sizes.

So, start off by filling in the woofer diameter and calculate W_{box}, then H_{box} and D_{box}, which are the width, height and depth respectively. Multiply these together to get the ideal volume, V_i, which is in litres. The tricky part now, is to work out the volume of the recess, V_r, without knowing the final width of the cabinet. Take W_{box} and add 30mm to it, this is purely an estimate and can be changed later on when the final dimensions have been established. In practice though, I've found it to be close enough not to make that much difference. Now add up all the individual volumes to get the loudspeaker total volume, LS_{tv} and combine with V_i, to get the total box volume, V_{box}. Add 10 %, which allows for all internal bracing and damping material. At long last, we get to work out the cabinet internal dimensions. Use W_{box} again, to calculate W_{act}, but now you have to play around with some figures to get V_{act} near or equal to V_{box}. Stick to whole numbers and round off the answers to the next highest number. Obviously a calculator with memory and square roots comes in handy here and it isn't too difficult to get the final values. Just remember that W_{act}, H_{act} and D_{act} are *internal measurements*.

Calculating port length.

At this stage, we have to determine the duct or tube length. See figure 13, "Port calculation chart", and fill in the known values: Q_{ts}, V_i, F_s, $F_{s/box}$ and $D_{i.d.}$. The last two refer to the frequency that the cabinet is tuned to and the inside diameter of the tube that you will be using. Two-inch (50mm) PVC tubing has an inside diameter of about 46mm, but measure to make sure of the exact figure. The term C_{duct}, is the **acoustical compliance** of a tube, that is, a characteristic of its geometry. When you have worked out your tube length, remember that it is measured from the front baffle outer face. Refer to figure 12 for details. You can use any size tube you want, the only limiting factors are: the space available on

3.

Box width - internal - $\mathbf{W_{box}}$:

Woofer diameter + 50mm = ...305.......+ 50 = $\mathbf{W_{box}}$ = ...*355*..........mm.

Box height - internal - $\mathbf{H_{box}}$:

W_{box} x 1.4142 = ...355...... x 1.4142 = $\mathbf{H_{box}}$ = ...*502*..........mm.

Box depth - internal - $\mathbf{D_{box}}$:

$$\frac{W_{box}}{1.4142} = \frac{355}{1.4142} =$$ $\mathbf{D_{box}}$ = ...*251*.........mm.

Ideal volume - $\mathbf{V_i}$:

$$V_i = \frac{H_{box} \text{ x } W_{box} \text{ x } D_{box}}{10^6} = 502 \text{ x } \frac{355}{10^6} \text{ x } 251 =$$

$\mathbf{V_i}$ = ...*44.73*....litres.

Woofer volume - $\mathbf{V_w}$:

$$V_w = \frac{\pi \text{ x } H_w}{3 \text{ x } 10^6} \text{ x } (R_w^2 + r_w^2) + (R_w \text{ x } r_w)$$

$$= \frac{\pi \text{ x } 120}{3 \text{ x } 10^6} \text{ x } (...137.....^2 + ...70....^2) + (....137...\text{x}...70.....)$$

$$= \frac{376.99}{3 \text{ x } 10^6} \text{ x } (.....23669.... + ...9590...........) =$$

$\mathbf{V_w}$ = ...*4.18*....litres.

Midrange volume - $\mathbf{V_m}$:

$$V_m = \frac{\pi \text{ x } R_m^2 \text{ x } H_m}{10^6} = \frac{\pi \text{ x } 52^2 \text{ x } 80}{10^6} =$$ $\mathbf{V_m}$ = ...*0.69*....litres.

Tweeter volume - $\mathbf{V_t}$:

$$V_t = \frac{\pi \text{ x } R_t^2 \text{ x } H_t}{10^6} = \frac{\pi \text{ x } 35^2 \text{ x } 11}{10^6} =$$ $\mathbf{V_t}$ = ...*0.043*....litres.

Fig. 11

3.

Mid/tweeter recess - $\mathbf{V_r}$:

$D_r = (W_{cone} - W_{flange}) - (M_{cone} - M_{flange}) - B_{front}$ = (48 - 10) - (...12.....-....11.....) - 16 =

D_r = ...*21*......mm

$W_r = W_{box}$ + 30mm = ...355.........+ 30mm =.......385.........mm

$H_r = H_{box} - W_{box}$ = ...502......... - ....385...... = ...117........mm

$$V_r = \frac{H_r \times W_r \times D_r}{10^6} = \frac{117 \times 385 \times 37}{10^6} =$$

V_r = ...*1.66*.liters

Loud speaker total volume - $\mathbf{LS_{tv}}$:

$W_v + M_v + T_v + V_r$ = ...4.18..... + ...0.69......... + ...0.043...... + ...1.66...... =

LS_{tv} = ...*6.6*.......litres.

Box total volume - $\mathbf{V_{box}}$:

$$\frac{V_i + L_{st} + 10\ \%}{10^6} = \frac{44.73 + 6.6 + 10\%}{10^6} =$$

V_{box} = ...*56.46*.......litres

Actual sizes - :

W_{act} = (wbox + **x**) = ...355........+......30....... = ...385..........

H_{act} = (W_{act} x 1.4142) = ...385......x 1.4142 = ...544..........

$$D_{act} = \left(\frac{W_{act}}{1.4142} \right) = \frac{385}{1.4142} = ...272.........$$

V_{act} = W_{act}........385......... x H_{act}......544......... x D_{act}......272.......x 10^{-6} =

(Add x amount of mm to W_{box} and re-calculate until V_{act} is equal to V_{box}. Try W_r first.)

V_{act} = ...*56.96* ......litres

W_{act} =.........*385*.........mm

H_{act}. =........*544*..........mm

D_{act} = ...*272*.........mm

Fig. 11 (cont.)

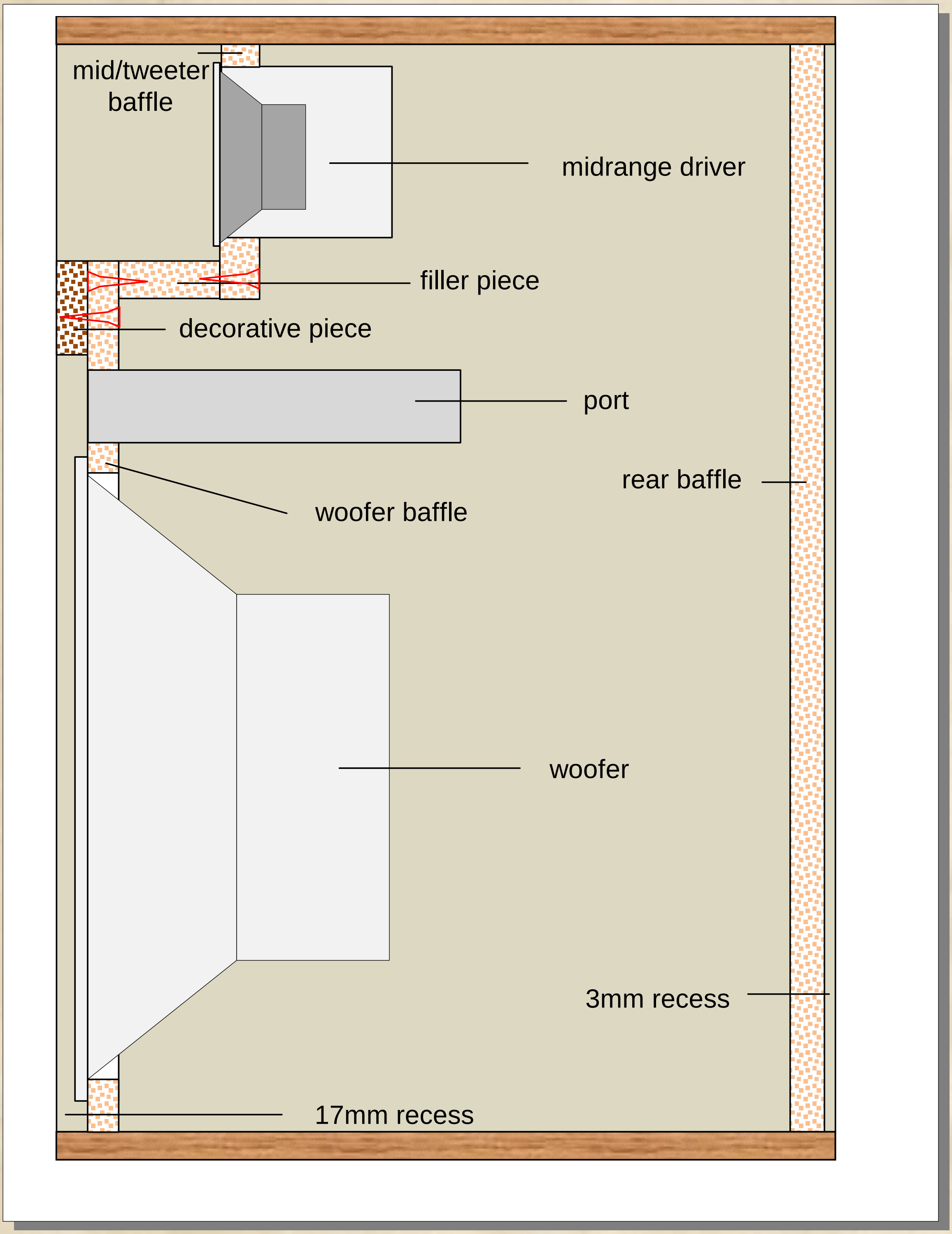
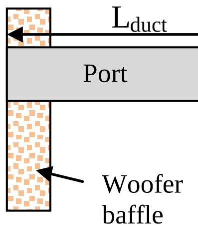

mid/tweeter baffle
midrange driver
filler piece
decorative piece
port
rear baffle
woofer baffle
woofer
3mm recess
17mm recess

Fig. 12

3.

Calculation of the tuned port.



Q_{ts} = ...*0.376*......

V_i = ...*44.73*...litres.

F_1 = ...*35*........Hz.

F_2 = ...*23*........Hz.

$F_{s/box}$ = ...*25*........Hz.(with Q_{ts} below .38, tune cabinet above Fs and if above .38 tune below F_s. Keep within F_1 and F_2.)

$D_{i.d}$ = ….*44*.......mm. (inside diameter of tube.)

$$C_{duct} = V_i \times \left(\frac{F_{s/box}}{53.25}\right)^2 = ...44.73..... \times \left(\frac{25}{53.25}\right)^2 = ...44.73..\times...0.2204...$$

C_{duct} =.....*9.86*.........

$$L_{duct} = \frac{0.768 \times (D_{i.d})^2}{C_{duct}} - 0.76 \times D_{i.d} = \frac{0.768 \times (44)^2}{9.86} - 0.76 \times .....44.....$$

$$= \frac{0.768 \times 1936}{9.86} - ...0.76......\times.....44... = ...150.79...-.....33.44..........$$

L_{duct} = ..*117.35*..mm.

Fig. 13

the woofer baffle and that it must be at least 50mm shorter than the inside depth of the cabinet. Only one duct is used, otherwise the cabinet would be completely de-tuned.

Wood sizes.

The next chart we come to is the "Speaker wood size chart", figure 15, where the final wood dimensions are calculated. This is where the thickness of the wood , plus any recess dimensions, are added. B_{front} and B_{rear} refer to the thickness of the baffles.

3D Acoustic Enhancer.

An innovation, which gives the sound a third dimension, is the 3D **Acoustic Enhancer**. See **figure 14** below. They are fitted in each recess corner.

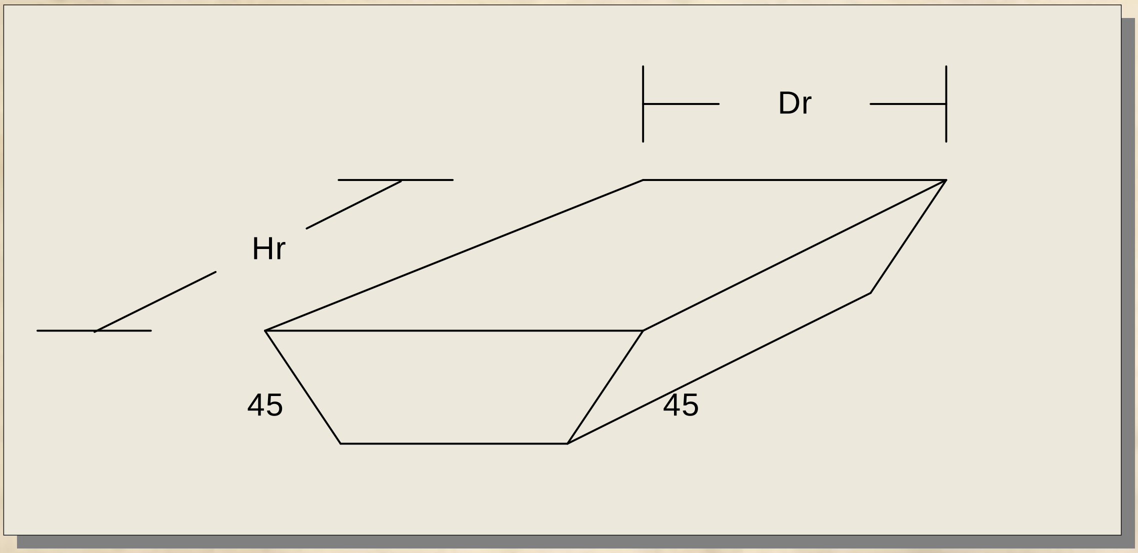


Fig. 14

The width of the enhancer is the same width as D_r , *which is the final width after cutting the 45-degree angles*! It is now just a matter of filling in the dimensions on the chart and determining the remaining wood sizes.

The **cleats** are the internal braces and serve two purposes, one is to hold the sides, top and bottom together and the second is to provide a mounting face for the baffles (the rear baffle is removable). See fig 16.
The "Materials list" can now be filled in, see figure 17, and is your shopping list for all the materials needed to build your speakers.

D_{final} = D_{act} + B_{front} + B_{rear} + grill recess + $B_{rear\ recess}$ =

....272..... + ...16........ + ...16........ + ...17...... + ...3......... =

D_{final} = ...*324*...mm.

H_{final} = H_{act} + top + bottom =

......544........ + ...16......... + ...16.......... = H_{final} = ...*576*...mm.

W_{final} = W_{act} + l/side + r/side =

.....385........ + ...16......... + ...16......... = W_{final} = ...*417*...mm.

Top and Bottom panels. W_{final} x D_{final} = ...*417*...... by ......*324*... mm.

Side panels. (H_{final} + X) x D_{final} = ...*576*...... by ....*324*.. mm.

X= extra amount for incorporating as stands.
This is optional.

Rear baffle. H_{act} x W_{act} = ...*544*..... by ....*385*.. mm.

Woofer baffle. W_{act} x W_{act} = ...*385*...... by ......*385*..mm.

Mid/tweeter baffle. (H_{act}- W_{act}) + B_{front} x W_{act} = (....544....-...385...) + 16 =

(...159..+ ..16..) x ....385.... = ...*175*..... by ....*385*..mm.

Filler. W_{act} x D_r = ...*385*..... by ....*21*..mm.

*Rear baffle centre brace. W_{act} - 38mm x 45mm

...385........- 38mm x 45mm = ...*347*..... by ....*45*..mm.

Note: B_{front} = the thickness of the panels (here 16mm).

*See Appendix B page 73
centre brace details.

Fig 15

3D Enhancer. $(H_{act} - W_{act}) \times D_r$ =

....544....... - ....385...... x ......37.........= ....**159**.... by ....**37**..mm.

Front decorative strip. W_{act} x 45mm = ...**385**.... by ....**45**..mm.
(The 45mm height depends on woofer size, so match accordingly).

Rear baffle side cleats. H_{act} x 19x19mm= ....**544**....by 19 x 19mm.

Rear baffle top & bottom cleats.
W_{act} - 38mm = ...385...........- 38mm = ...**347**....by 19 x 19mm.

Woofer baffle side cleats. H_{act} - 16mm =
385 - 16mm = ...**369**....by 19 x 19mm.

Woofer baffle bottom cleat.
W_{act} - 38mm = ...385.......... - 38mm = ...**347**....by 19 x 19mm.

Mid/tweeter side cleats.
$(H_{act} + W_{thickness}) - W_{act}$ = (544 + 16) - ..385..... = ...**175**....by 19 x 19mm.

Mid/tweeter top cleat.
W_{act} - 38mm = ...385.........- 38mm = ...**347**....by 19 x 19mm.

Corner cleats-bottom.
D_{act} - 38mm = ...272....... - 38mm = ...**234**....by 19 x 19mm.

Corner cleats-top. $D_{act} - (D_r$ + 38mm + 16mm)
.......272..... - (...37... + 38 + 16) = ...**181**....by 19 x 19mm.

*H-brace cross piece.
W_{act} - 38mm = ...**347**....by 19 x 19mm.

*H-brace ends.
D_{act} - 38mm = ...**234**....by 19 x 19mm.

*See Appendix B page 73 for H-brace details.

Fig 15 (cont.)

3.

Fig. 16

I manufacture the baffles, 3D enhancer and filler piece from plain 16mm chipboard and then paint them matt grey/charcoal, which matches the colour of the cones of the drivers, but as I've said before the final choice is yours. The H-brace is optional and is there to provide additional stiffening to the sides, preventing **vibrational flexing**.

Assembly techniques.

Once you have all the pieces cut to size, start drilling the screw holes in the cleats. The woofer baffle side and bottom cleats, the mid/tweeter top and side cleats, as well as the four corner cleats get holes drilled through two adjacent sides. The short pieces get 3 holes on one face and 2 holes on the other face. The longer pieces get 4 and 3 holes respectively. The rear baffle sides, top and bottom cleats, get holes drilled through one side only, 5 on the long pieces and 4 on the short ones. This is because the rear baffle screws onto these cleats from the outside, whereas all other baffles get screws from the inside. See exploded view.

Prepare a watery glue mixture by diluting some wood glue with water and apply to the 45-degree ends of the panels. This allows the chipboard to absorb the mixture quite deeply and helps to make a much stronger joint. While this is soaking in, you must fit the cleats to their respective panels. Glue and screw the front and rear baffle side cleats to the left and right side panels, remembering to position them to make allowance for the recesses. On mine, the rear baffle cleats were 19mm from the edge and the front ones 33mm, that is, 3mm for the recess plus 16mm for the baffle thickness on the rear edge and 17mm (the thickness of the decorative piece), plus 16mm, from the front edge. Do the same when fitting the front and rear baffle top and bottom cleats. Leave the mid/tweeter side and top cleats for now. Fitting the four corner cleats requires a bit more effort by carrying out a mock assembly, that is, by assembling and clamping everything together without glue. (Torqcraft manufacture a picture frame clamp consisting of four plastic corner pieces and a strap and is quite useful here). Fit the rear baffle as well, to help square the whole lot up. Now position the corner cleats one by one and mark their positions, or if you want, glue and screw them onto the top and bottom panels. An electric screwdriver is a handy tool for doing this.

Unclamp everything and apply glue to the nearly dry panel 45-degree ends and corner cleats, then making sure that each panel is facing the right way round, clamp everything together again. Now screw the corner cleats to the side panels to help secure the whole assembly. I put the speaker cabinet face down and temporally fit the rear baffle to aid in keeping the box square, making sure that there is no glue on the cleat faces, which would make the baffle's removal difficult afterwards. After about six to eight hours you can remove the clamps and rear baffle.

Speaker and port orientation.

While waiting for the glue to dry, cut the speaker and port holes in the baffles, checking that the midrange and tweeter are evenly spaced on their baffle, allowing room on the ends, where the 3D Enhancer's go. The woofer cut-out is offset so that the lower end is about 20mm from the lower edge. (This is to allow the decorative strip to fit above the woofer).

Wood type : ....16........mm. Chipboard with ....Oak............veneer.

Top and bottom ....417.......mm by ......324........mm 4 off.

Sides ....576.......mm by ....324........mm 4 off.

Decorative piece ......385........mm by ....45.........mm 1 off.

Wood type : ....16...............mm Plain chipboard or ....veneer.

Rear baffle ....544....mm by ....385.......mm 2 off.

Woofer baffle ....385....mm by ....385.......mm 2 off.

Mid/tweeter baffle ....385....mm by ....175......mm 2 off.

Filler piece ....385....mm by ....21......mm 2 off.

3D Enhancer ....159....mm by ....37......mm 4 off.

Wood type : 19mm by 19mm pine.

Rear baffle side cleats ....544........mm 4 off.

Rear baffle top and bottom cleats ....347.......mm 4 off.

Woofer baffle side cleats ....369.......mm 4 off.

Woofer baffle bottom cleat ....347.......mm 2 off.

Mid/tweeter side cleats ....175.......mm 2 off.

Mid/tweeter top cleat ....347.......mm 2 off.

Corner cleats - top ....181.......mm 4 off.

Corner cleats - bottom ....234......mm 4 off.

H-brace cross piece ....347......mm 2 off.

H-brace ends ....234......mm 4 off.

Fig. 17

Wood type :	45mm by 19mm pine.		
Rear baffle centre brace		.........347..........mm	2 off.
Wood type :	10mm by 10mm pine.(Measure actual openings.)		
Grill frame top and bottom		.........383..........mm	8 off.
Woofer grill frame sides		.........318..........mm	4 off.
Mid/tweeter grill frame sides		.........137..........mm	4 off.
Wood type :	4mm Hardboard.		
Woofer grill	........383...........mm by	.........338.........mm	2 off.
Wood type :	Iron on veneer to match chipboard		.....10......m.
Screws :	Chipboard 25mm long, countersink		126 off.
Screws :	Self-tapping 25mm long, roundhead.		40 off.
Bolts :	Cuphead for speaker mounting 6 x 25mm.		.....28..off.
Grill cloth :		..........1.......... running meter.	
Carpet underfelt :		..........1...........running meter.	
Speaker terminals :			2 off.
Port :	PVC. tubing .....50......mm OD	......300......mm.	
Wood glue :			.....1.....bottles.
Contact adhesive :			.....1.......tubes.
Epoxy glue - clear :			.....1......packs.
Sealing compound :			.....1......tubes.
Polyurethane varnish - matt :			....1.......litres.
Battleship grey lacquer paint :			.....1.......litres.

Fig 17 (cont.)

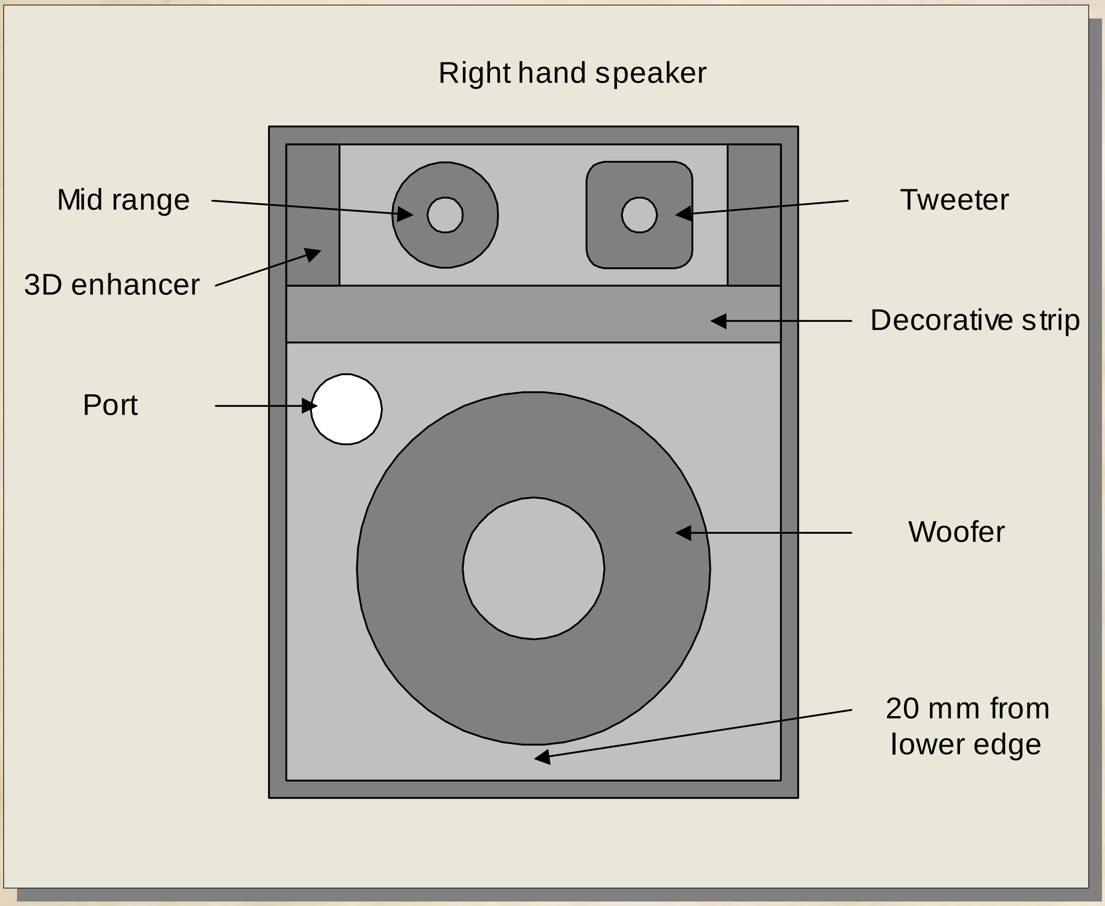


Fig. 18

The left hand speaker cabinet gets its tweeter fitted on the left hand or outboard side of its baffle and vice-a-versa for the right hand cabinet. The port holes are then cut out on the opposite side to the tweeters, on the woofer baffle. See **figure 18** above. The tubes can then be fitted and bonded in with clear epoxy and left to dry. I then router a radius on the inside diameter of the tube, as it gives a neater finish.

Assemble the front baffles by drilling 4 holes along the woofer baffle top face and one face of the filler piece. Then glue and screw the filler piece to the mid/tweeter baffle using figure 12 as a reference. Now glue and screw this assembly to the woofer baffle. When dry, temporarily fit the now completed front baffle into the cabinet and mark, or glue and screw the mid/tweeter side and top cleats in.

To finish the cabinet edges off, iron-on **wood veneer** is used. The ends are cut to 45 degrees and I find a good sharp pair of scissors work well here. It is easier if you iron them on, one at a time, as this allows you to get a perfect join, which results in a neat finish. Unfortunately, the veneer is wider than the chipboard, so a little care is needed to trim the excess off. To do this, take a coarse grit sandpaper on a rubber block and gently sand two or three times, holding the block at an angle, along the edge of the panel, then peel the unwanted veneer off. Finish sanding the edge with a finer sandpaper. If you make a mess, just run the iron over the edging and while hot peel the piece off and re-do.

Now is a good time to paint the baffles and the insides of the cabinet recesses and then when dry, glue and screw the front baffle in. All that remains now, is to fit the front decorative piece and glue the 3D acoustic Enhancer's into the corners, to conclude the main assembly.

Finishing touches.

A light sanding to get rid of all dirty marks and scratches is followed by a couple of coats of matt **polyurethane varnish**. A trick to get a real smooth finish, is to take 1000 wet&dry paper dipped in some soapy water and give a light sanding to the first coating to get rid of all the little dust knobs. Then wipe dry and give a final thin coat of varnish, making sure that there are no runs or brush marks. The next step, is to make sure that all the **joints** *are airtight*. Use an **acrylic filler** to seal all the inside edges. When you are satisfied, line the inner sides, top, bottom and rear baffle of the cabinet with extra-heavy duty carpet **underfelt**, by either gluing or stapling it on. Cut the rear baffle underfelt smaller than the panel by the amount of twice the cleat width, so that the panel can be screwed down flat onto the cleats. The front baffle does not get lined. Drill the screw holes in the rear baffle, 4 evenly across the top and bottom and 6 on each side, making sure that they will miss the screws securing the cleats inside the cabinet. Lay the speaker cabinet face down and fit the rear baffle. Now drill pilot holes into the cleats, that is, small holes that the fasteners screw into so that the wood doesn't split. Use round head self tapping screws for fastening the rear baffle. All other screws are countersink chipboard screws. I use spring-loaded, lever action, quick-connect terminals, which I screw onto the rear baffle after drilling the holes for the hook-up wire to pass through. Speaking of wire, use house mains cabling, the red and black ones, for the hook-ups to the speaker and crossover networks. Bolt the speakers onto the baffles using cuphead bolts, nuts and washers with a bead of silicone sealer under the flanges to ensure an airtight seal.

Speaker grills.

I personally don't have **speaker grills**, but if you've got kids that you can't control, then I'd suggest fitting them. The easiest way to make them is to take measurements of the openings only once the cabinets are finished. Cut a piece of 4mm hardboard, about 2 mm smaller than the woofer baffle and cut out holes the same size and position as the speaker and port. Now cut four 10 x 10mm square battens, then glue and nail them together to form a frame (butt joints), which is glued onto the hardboard perimeter. When dry, paint the assembly matt black. Check to see that they fit into the recess with sufficient gap to accommodate the **grill cloth**. If all is well, lay the grill cloth face down on the floor, preferably a carpeted one, and put the grill frame face down onto the cloth, making sure that the weave or pattern is aligned with the edges, then cut with sufficient overlap to fold over the battens. Start by folding the cloth over one side and stapling it down. Then do the opposite side, but pull the cloth reasonably tight before stapling. Repeat this with the top and bottom ends. A piece **of Velcro tape** glued to each frame corner and matching point on the woofer baffle is sufficient to hold it in place. You might have to first glue a thin strip of wood onto the baffle before gluing the Velcro tape on, to ensure that the grill fits flush with the edges. The mid/tweeter grill consists of just a frame made from 10x10mm battens, also glued and nailed, but without any hardboard and then covered with grill cloth, the same way as you did for the **woofer grill**. The woofer baffle needed the hardboard to give support to the grill cloth and to stop it from flapping back and forth due to its large size. To secure the **mid/tweeter grill** into the recess, requires that two or four wooden blocks be glued to the inside of the recess, for the frame to butt against. Also use Velcro tape to secure the grill to the blocks.

Summary.

1. W_{act} , H_{act} and D_{act} are internal measurements.
2. Port length includes the front baffle thickness. i.e. It is measured from the outside face.
3. Make sure that all joints are airtight. Leaks will de-tune the cabinet.
4. The front woofer baffle does not get any damping material applied to it. Each speaker cabinet gets it's tweeter fitted on it's outboard side and its port fitted on the opposite inboard side.

Chapter 4.

Crossing over.

If you thought that the cabinet dimensions were important, then know that the **crossover network** is just as important. Not only does it split the frequencies between the drivers, but it also determines the power going to them. Without a network, you would simply blow the tweeter. If you look inside a so-called "hi-fi" speaker, you would be very surprised, as sometimes all there is, is a capacitor connected to the tweeter. This not only applies to hi-fi speakers, but to car ones as well. A good quality low loss network is essential no matter where it is used. You can use this crossover in your car's system too.

Type of network.

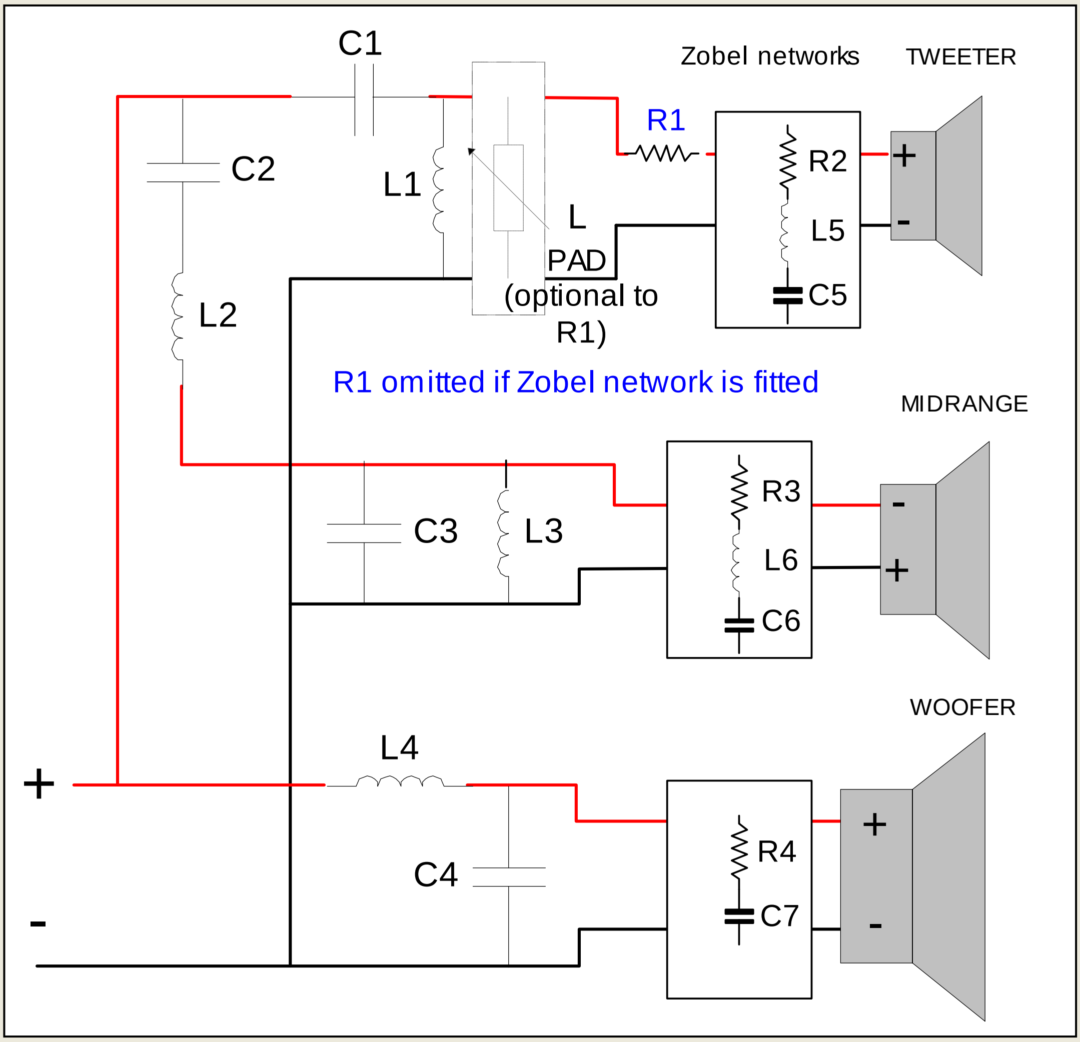
The **network** we are going to build is called a ***three-way, second order Linkwitz/Riley parallel network***, with a 12-dB cut-off rate. By the way, there is nothing stopping you from building a two way speaker nor from using any size woofer that you want, just fill in the charts with the intended sizes. Obviously if you build a two-way network, all you do is omit the midrange portion of the circuit and change the crossover point.

The following crossover is the classic textbook type. I am not going into any detail on how crossover networks operate because there are enough books covering the subject in greater depth. What is important and I mentioned it in an earlier chapter, is that a loudspeakers impedance changes with frequency. This is plain to see in the impedance graph in figure 7. Another very important point to note here is that a three-way crossover network inverts the signal to the midrange driver, so you must reverse the connections to the speaker. See figure 19 for details.

Crossover points.

A spectral analysis of a typical piece of music shows that the bulk of the power is concentrated in the 500 Hz region. A typical voice ranges from 500 Hz to 2000 Hz and a typical hi-fi system from 20 Hz to 20 000 Hz (10 octaves). If this is split between the woofer and tweeter, then the crossover point would be about 784 Hz. A single driver cannot cope with the full range of sound at high powers, without causing **Doppler** and other distortion. This distortion is a result of the change in pitch of the

4.



Note midrange polarity reversal

Fig. 19

high frequencies as the woofer cone moves in and out. The cone also cannot cope with two low notes of differing polarities, that is, if one note causes the cone to move outwards while the other moves it inwards, without distorting. The choice then would be to keep the woofer below the voice range, which has a lot of dynamic power of its own, to less than 500 Hz. This is the professional choice and is the one I have chosen. But feel free to experiment. Top C (4186 Hz) on the piano, still has a fair amount of energy in it, so I have chosen 5000 Hz as the upper or tweeter crossover point which is about the limit, maybe dropping to 4500 Hz. Now, due to the fall off of power as the crossover point is reached, the beauty of the three-way network comes to the fore and that is to let the midrange operate between the two crossover points of 500 Hz and 5000 Hz. In a two-way system, the crossover point is usually 2000 Hz and as a result the woofer has to cover a greater frequency range and the tweeter must handle more power. Using the impedance data from figure 8, calculate the capacitor and inductor values on "Crossover Network Calculation Chart" in figure 20. With modern drivers, Zobel networks are a necessity and their aim is to keep the voice coil impedance constant. Therefore check your impedance curve chart and use an impedance that falls on the flattest part of the curve. On my chart this is at about 100 Hz and is equal to 8.2 Ω. This then does not upset the crossover and actually makes it work more efficiently. If you already have loudspeakers and they don't sound good, you can always use this info to tweak them.

Capacitors and inductors.

A crossover network consists of **capacitors** (non-polarised) and **inductors** (coils) to control the power and frequency to the drivers. Basically a capacitor blocks low frequencies and an inductor blocks high ones. Using one of each, that is, one capacitor on the tweeter and one coil on the woofer, is called a **first order network** and has a 6-dB per octave cut-off slope. Adding an inductor to the tweeter and a capacitor to the woofer, makes it a **second order network** with a 12-dB slope. This is the preferred choice, as going any steeper is not only more expensive, but introduces **transient distortion**, that is, the blurring of notes when the speaker encounters sudden changes in signal. Audio grade **polypropylene** capacitors are the best ones to use, but unfortunately do not come in very high values, usually to about 4.7 µF. You can either connect them in parallel to get higher values or use special non-polarised electrolytic capacitors that are much cheaper. Whatever you use, make sure that the **voltage rating** is high enough for the power output of your amplifier. The following table refers :

Power - Watts rms.	50	100	150	250	500
Voltage - 4 ohm load	20	28	35	45	63
- 8 ohm load	28	40	50	63	90

Doubling the Voltage in the table above gives a good safety margin.

4.

Crossover points: ....500......&.....4500........ Date: ....22-3-93.........

Z_w* = ...8.64...... Z_{mh} = ...11.18..... Z_{ml} = ...7.8....... Z_t = ...7.38......

Woofer :

$$L4 = \frac{Z_w}{\pi \times F_L \times 10^{-3}} = \frac{8.64}{3.14 \times 500 \times 10^{-3}} = \text{.......}\mathbf{5.50}\text{.....mH}$$

$$C4 = \frac{1}{4 \times \pi \times Z_w \times F_L \times 10^{-6}} = \frac{1}{12.56 \times 8.64 \times 500 \times 10^{-6}} = \text{.......}\mathbf{18.42}\text{......uF}$$

Midrange :

$$L2 = \frac{Z_{mh}}{\sqrt{2} \times \pi \times (F_h - F_L) \times 10^{-3}} = \frac{11.18}{4.4445 \times 4} = \text{........}\mathbf{0.629}\text{....mH}$$

$$L3 = \frac{Z_{ml} \times (F_h - F_L)}{\sqrt{2} \times \pi \times F_m \times 10^{-3}} = \frac{7.8 \times (4500 - 500)}{4.44445 \times 2250} =$$

(Where $F_m = F_h \times F_L$
....4500...x....500.....
=......2250000.............)

$$= \frac{31200}{10000.232} = \text{........}\mathbf{3.12}\text{......mH}$$

$$C2 = \frac{F_h - F_L}{\sqrt{2} \times 2 \times \pi \times Z_{mL} \times f_m \times 10^{-6}} = \frac{4500 - 500}{8.889 \times 7.8 \times 2.25} =$$

$$= \frac{4000}{156.00195} = \text{.........}\mathbf{25.65}\text{.....uF}$$

$$C3 = \frac{1}{\sqrt{2} \times 2 \times \pi \times Z_{mh} \times (f_h - F_L) \times 10^{-6}} = \frac{1}{8.889 \times 11.18 \times 0.004} =$$

$$= \frac{1}{0.3945} = \text{.........}\mathbf{2.51}\text{.......uF}$$

Tweeter :

$$L1 = \frac{Z_t}{\pi \times F_h \times 10^{-3}} = \frac{7.38}{14.14} = \text{.......}\mathbf{0.522}\text{.....mH}$$

$$C1 = \frac{1}{4 \times \pi \times Z_t \times F_h \times 10^{-6}} = \frac{1}{0.05657 \times 7.38} = \text{.........}\mathbf{2.39}\text{.......uF}$$

* Note: Use value of R4 if using an impedance equaliser – see page 64.

Fig. 20

4.

Inductors.

Inductors are coils of copper wire wound onto bobbins, or coil formers. See **figure 21** below for details. The inductance of a coil depends on the number of turns, as well as its cross sectional area and ranges from about 0.001 to 6.5 mH. This is one of the more difficult areas of speaker construction and that is the winding of the coils. To prevent insertion losses and to be able to withstand high powers, 1mm enamelled **copper wire** is used and all data and tables refer to this diameter. The best place to get copper wire is from your local motor re-winding works and about 4kg is about enough.

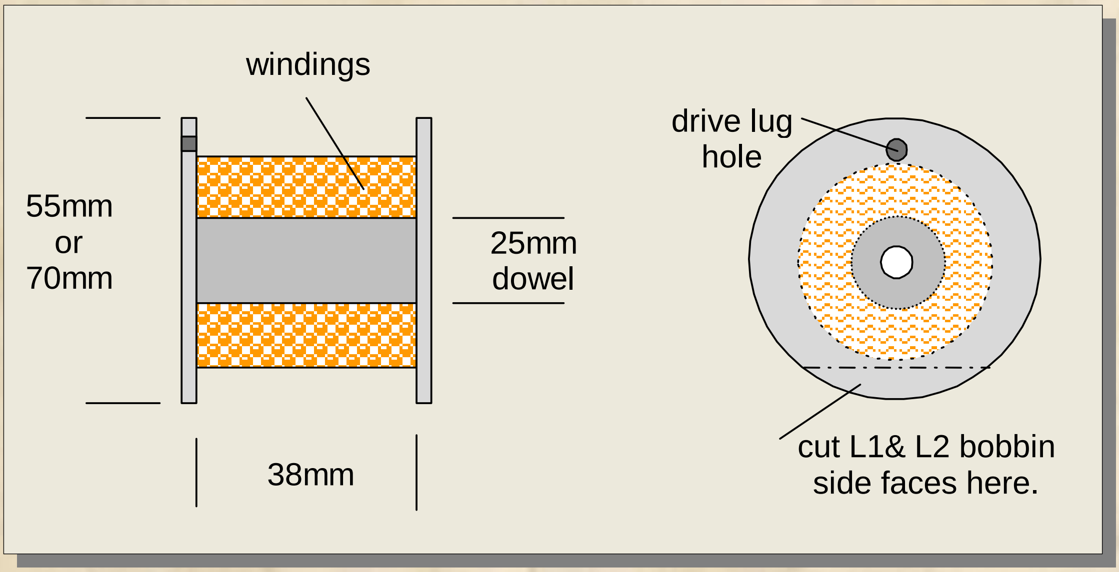


Fig. 21

Winding coils.

I have not found a source for the plastic **bobbins**, so I make mine out of wood. Cut the discs from 4mm plywood, about 55mm for L1 and L2 and 70mm for L3 and L4, using a hole saw fitted to your drilling machine. The centre part of the bobbin is 25mm dowel stick or broom handle, with a hole the same size as that of the hole saw's drill, through its centre and cut to a length of 38mm. At this stage I must point out that the bobbin

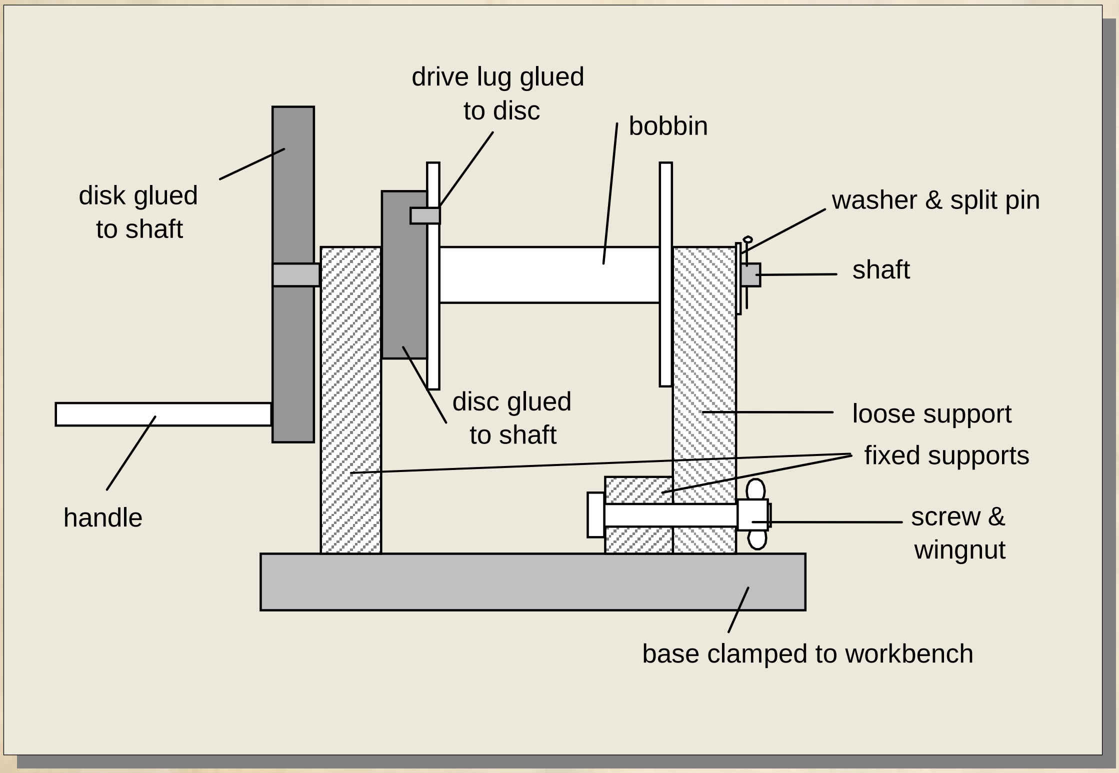


Fig. 22

must have ***no metal parts*** to it, as this affects the inductance.

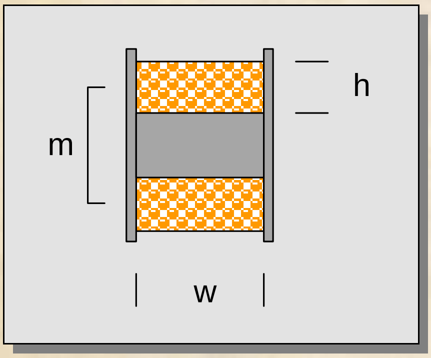
Assemble the bobbin by gluing the two discs to the centre former and temporally bolting it together until it is dry. Drill a locating hole on one cheek or side that will engage with a driving lug (a dowel) fitted on a winding jig. I had to make a winding jig to help me wind coils and you can easily make one yourself from scrap wood, see **figure 22** above. When you start winding, make sure that **all** coils are wound in the *same direction* and from the *same side*, that is, decide if you are going to wind them *clockwise* or *anti-clockwise* or start from the *left* or *right*. Before starting to wind the wire on, score a groove on the inner face of the bobbin at a tangent from the centre, outwards to the edge, so that the first winding starts as close to the side as possible. The wire actually lies in the groove, and make the start wire long enough, ± 120mm, as it is has to reach the **terminal block** where all the connections are made. Also remove about 10mm of the enamel from the end of the wire and then bend it over the edge of the bobbin side, so that it doesn't get in the way when the winding process starts.

The following formulae are used to determine the inductance and number of turns:

$$N = \sqrt{L \text{ x } \left(\frac{3m + 9w + 10h}{7.87 \text{ x } m^2}\right) \text{x} 10^6} \quad \text{turns.}$$

m = mean diameter. w = width of bobbin. h = height of windings.
N = number of turns L = inductance in milliHenries.

All dimensions in mm.



Note:
In practice, the actual number of windings is about 5 % less than the ideal, as determined in the formula, due to the difficulty in keeping the windings neat and close wound.

$$L = \frac{7.87 \text{ x } m^2 \text{ x } n^2}{3m + 9w + 10h} \text{ x } 10^{-6} \text{ mH.}$$

Refer to the "Inductance chart", figure 23, for the number of turns required. When winding the coils, make sure that the windings are tight and close wound, that is, there are no gaps between the windings, do not wind them on randomly. My DMM has the facility for measuring inductance, so I wind on the number of turns, as determined from the chart. Then, connecting one lead of my DMM to the cleaned start winding and using a sharp object like a knife blade, with the other lead connected to it, I pierce the enamel to get a reading. I then add or remove wire as required. Don't worry if you do not have a DMM that measures inductance, the chart is accurate enough. To keep the windings from coming undone, wrap fibreglass insulation tape, or any similar high temperature tape, around the coils on the bobbin. Also mark each coil with its position and value, to avoid confusion when assembling the network later on.

4.

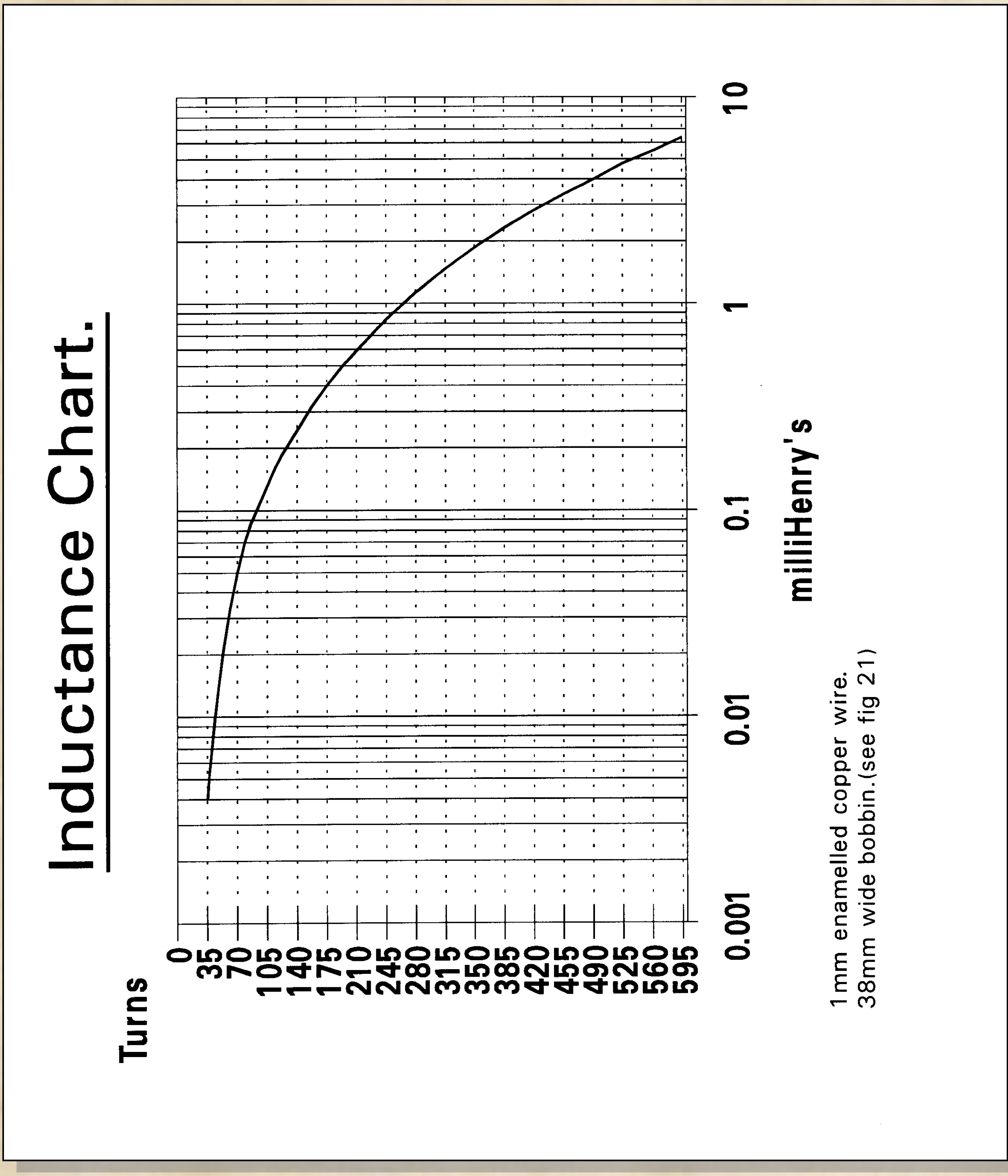

Inductance Chart.
Turns
0
35
70
105
140
175
210
245
280
315
350
385
420
455
490
525
560
595
0.001
0.01
0.1
1
10
milliHenry's
1mm enamelled copper wire.
38mm wide bobbin.(see fig 21)

Fig. 23

4.

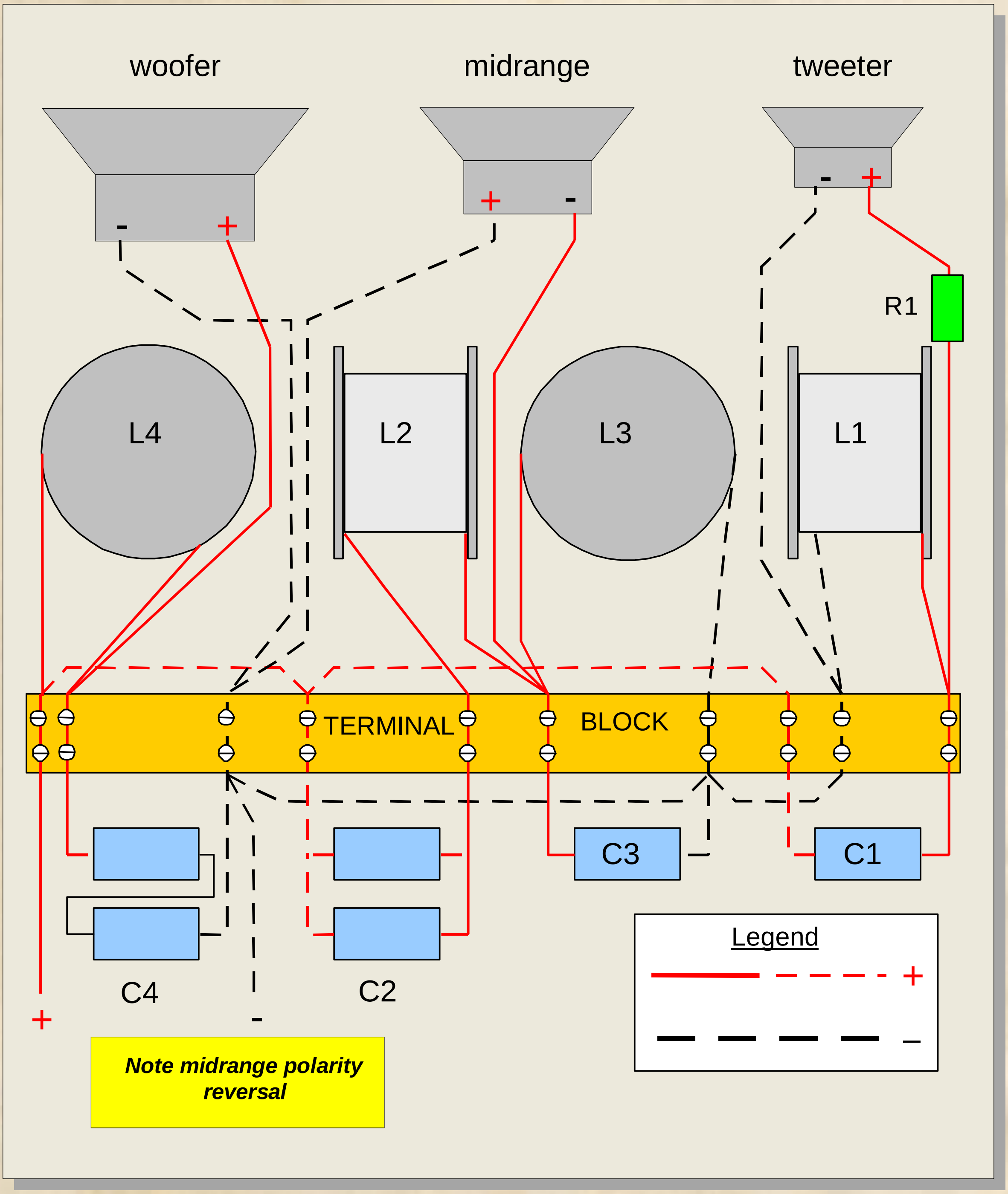

woofer
midrange
tweeter
-
+
+
-
-
+
R1
L4
L2
L3
L1
TERMINAL
BLOCK
C3
C1
C4
C2
+
-
Note midrange polarity reversal
Legend
+
_

Fig 24

4.

Assembling the crossover networks.

The easiest way that I found in assembling the network, was to glue the coils onto a piece of wood and to use a chocolate block, that is, one of those long plastic terminal blocks with a double row of screws, to connect the wires to. See figures 16 and 24 for a general layout. To prevent **magnetic interaction** between adjacent coils, mount them at right angles to each other. Start by hot gluing L4 face down, then L2 standing upright, (if you look at figure 21 you will see that bobbins L1 and L2 get segments cut off the side discs, so that they may stand upright) and then L3 face down, with L1 standing upright. The capacitors are mounted directly to the terminal block, with jumper wires connecting the components where necessary. The whole assembly then gets screwed down on top of the damping material, which acts as a shock absorber, at the bottom of the speaker cabinet. You can also use point to point wiring if you wish, but I try and avoid having to solder the joints, as they tends to become brittle and come loose after a while.

You will notice that C2 consists of two capacitors in parallel, a 15 uF and a 10 uF giving a total of 25 uF. I solder the one to the other before connecting to the terminal block. R1 is a damping resistor sometimes used for controlling the rise in impedance of the tweeter as the frequency rises and is normally 2R2 ohms @5w, but rather use a Zobel impedance filter.

Capacitor and resistor combinations.

Sometimes it is the value of available capacitors that will determine the crossover points for the crossover network. I juggle the figures around so as to obtain a capacitor value as close to that of a standard value. For example you may only be able to buy 2µf2, 2µf7, 3µf3, 4µf7 in polyester or polypropylene but we need up to 48µf and I couldn't bear to parallel ten 4µf7 caps to get this value. Bipolar (non-polarised) caps come in values ranging from 2µf2, 4µf7, 22µf, 47µf, 100µf and 220µf and using my calculator, I try to get as near to the value required with as few parts as possible, by putting them in series or parallel. Remember capacitors in parallel add in value, as do resistors connected in series. Resistors in parallel decrease in value as do capacitors connected in series. With capacitors in series, the total value will be less than the lowest capacitor, which also applies to resistors connected in parallel :-)

To work out the values required, use the following formulae:

For parallel capacitors: $C_T = C_1 + C_2 \ldots\ldots + C_6$

For series capacitors: $C_T = \dfrac{C_1 \times C_2}{(C_1 + C_2)}$ or $\dfrac{1}{C_T} = \dfrac{1}{C_1} + \dfrac{1}{C_2} + \dfrac{1}{C_3} \ldots + \dfrac{1}{C_6}$

For parallel resistors: $R_T = \dfrac{R_1 \times R_2}{(R_1 + R_2)}$ or $\dfrac{1}{R_T} = \dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} \ldots + \dfrac{1}{R_6}$

For series resistors: $R_T = R_1 + R_2 \ldots + R_6$

For example, I needed C5 to be 39µf, so plugging the following values into the formula gave me:
(When selecting values, try the nearest value *above* the one you require, which in my example was 47µf.)

Note: If this answer is not near a standard value, try going up one more with the first cap.

$$C_x = \frac{39 \times 47}{(47 - 39)} = 229\mu f$$

taking 220µf as the closest to this and reworking in the formula gives:

$$C_T = \frac{220 \times 47}{220 + 47} = 38.72\mu f.$$

So, a 47µf cap in series with a 220µf cap gives 38,72µf which is close enough to 39, considering that the tolerance of the caps is between 10% and 20%. Follow the same procedure for calculating the resistors and you usually need only two connected in either series or parallel. For example, $R_a = 7.2\Omega$, so use a 3.9Ω and 3.3Ω in series or for $R_b = 2.23\Omega$, use a 6.8Ω resistor in parallel with one of 3.3Ω giving a total of 2.22Ω, also close enough considering the tolerance of the devices. Non polarised electrolytic capacitors have high internal resistance, called high **ESR**, which supposedly affects the frequency response and is why some people prefer polypropylene types, which are very expensive. To overcome this, connect a 0.1µF/100v polyester capacitor in parallel with the bipolar cap, usually where the signal goes through the cap i.e. at C1 and C2.

4.

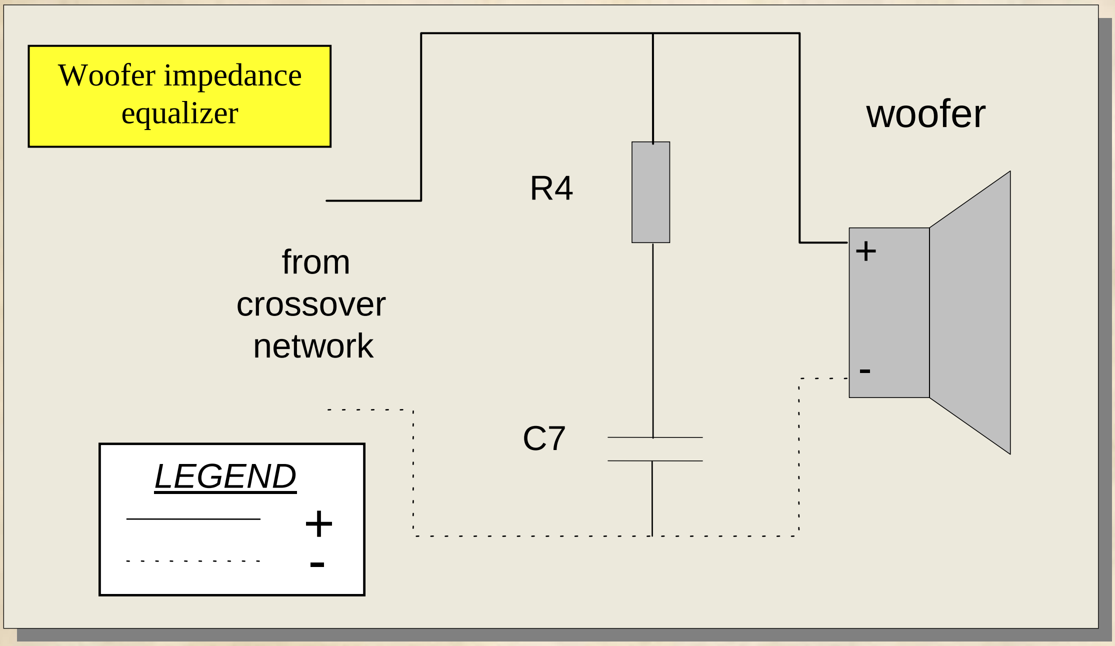


Fig. 25

Woofer Impedance Equalizer.

R4 = ……**6.8**…….Ω   C7 = ……**38**………µF

F_5 = …615...Hz. (see data chart)

Where $L_e = \dfrac{R_e}{2 \times \pi \times F_5} \times 10^3 = \dfrac{6.8}{6.28 \times 615}$ = ……..1.76……..mH.

C7 = $\dfrac{L_e}{R_e^2} \times 10^3 = \dfrac{1.76}{(6.8)^2} \times 10^3$ = ………..38……..µF.

R4 (Use a standard 5watt value close to 8Ω = ………..6.8……..Ω.
or use R_e. Check the impedance curve as
a reference and aim to get as straight a line as possible)

Fig. 26

4.

Summary.

1. Use non-polarised capacitors with a voltage rating high enough for your amplifier.
2. The charts are based on 1mm diameter enamelled copper wire.
3. 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.
4. Mount adjacent coils at right angles to each other, with sufficient space between them to prevent magnetic interaction.
5. Fit an impedance equalizer to woofers that have a steep rise to their impedance curve.
6. Fit a 100n polyester capacitor in parallel with bi-polar types to lower the ESR (equivalent series resistance).

Chapter 5.

A test in time saves.....

Not having super amazing sensory listening powers, prevents me from being able to detect distortion below 1%, so I don't worry too much about carrying out any detailed or special tests. Besides, I don't have thousands of Rands worth of test equipment or a special laboratory that has an acoustically set up sound room with 2 meter thick walls and critically damped floor, to use as a listening room. (Nor does anyone else in South Africa!)

Speaker cables.

So, we will test our speakers by doing a few simple basic tests. First off, measure the **d.c. resistance** of the completed cabinet, to ensure that the resistance is not below that of a single speaker i.e. 6-8 ohms, which would indicate that you have a wiring problem and could damage your amplifier.

Before going any further, let's broach the testy subject of speaker cables. Reading all the hype about **inter-connects** and speaker cables never ceases to amaze me. Some people out there sure have damn good ears, especially when they can hear the difference between ordinary copper wire and oxygen free silver plated wire. Radio Electronics carried out a comprehensive test on all types and sizes of cable, from telephone wire to heavy-duty welding cable and could detect no significant signal loss or distortion. You just have to look at the thickness of the leads on capacitors or the wire used in the construction of our coils. The main factor in determining wire diameter, is the **load** that it has to carry over distance. The following formula refers:

$$I = \sqrt{\frac{P}{R}} \text{ amps}$$

For example a 100 watt amp driving an 8 ohm load, $I = \sqrt{\frac{100}{8}} = 3.5$ amps.

As a rule of thumb, use 19 SWG (.75mm^2) gauge wire for 100 watts into 8 ohms at up to 5 meters in length. Go down two gauges per 100 watts, halving of the load or lengths exceeding 5 meters (1.25mm^2). I use 179 strand twin flex, 5 meters long. Next, connect your loudspeakers to the amplifier and using your audio generator as an input, sweep up and down the frequency range listening closely to each speaker and seeing that they operate more or less within the range that you designed them for. With a low frequency selected, turn the volume up and listen for any rattles, buzzes or air leaks. Also feel the sides, top and bottom for excessive **panel vibration**, which might require additional bracing. If all is well, sit back and play your favourite c.d., as your ears are going to be the final judge.

I used the c.d. "Communiqué " by Dire Straits, as it is sufficiently laid back to allow one to evaluate each instrument individually and there is also a mean bass drum finish to "News", that gives you the feel of the skins vibrating as they are struck. The symbols should sound crisp and clear, not faint little hisses in the background. If your tweeters are too loud (bright) and your amplifier doesn't have a decent treble control, then you might have to fit an **"L" pad** between the network and the tweeter. This is a special potentiometer that has a constant 8-ohm resistance regardless of its selected position. It can be mounted on the front or rear baffle, depending on its size of course, as it comes supplied with an escutcheon plate that has graduations marked on it, just follow the instructions supplied with it.

<u>Room acoustics.</u>

Obviously the acoustics of your room are going to play a big part in how your system is going to sound, as chairs and curtains etc. have a **damping effect**. Therefore it is not possible for me to say too much more on this subject, other than don't go overboard in trying to re-arrange the household, I mean what will the wife say? The speakers should be quite far apart, at least 3 meters, otherwise the stereo sound stage disappears.

<u>Speaker stands.</u>

The size and style of your **speaker stands** is entirely up to you, as you might want to match them to existing furniture or whatever. I find a height of about 350mm just right, as this puts the speaker's centre axis in line with the chair that I sit in. Placing them directly on the floor tends to cause a loss in bass response due to the absorption of the sound by the carpeting and floor. There will always only be one listening position and that is dead centre between the two speakers. The distance from the rear of the speaker to the back wall will depend on your circumstances but should be about 300mm to 500mm and about the same from any side walls.

Test c.d.

There are special test c.d.'s available with a number of different tests on them, including pink noise, phase checks, voices, instruments etc., which will give you a good idea on what to base your own parameters on.

Some tweeters and midrange speakers tend to resonate annoyingly at their resonant frequency and may be improved with a **Zobel notch filter**, see **figure 27** below, that you insert across the driver leads. R_n is the speaker's DC resistance R_e, which you can measure with your DMM and F_n you get from the Impedance Data Chart for the applicable speaker (it's resonant frequency *or* the frequency you need to control).

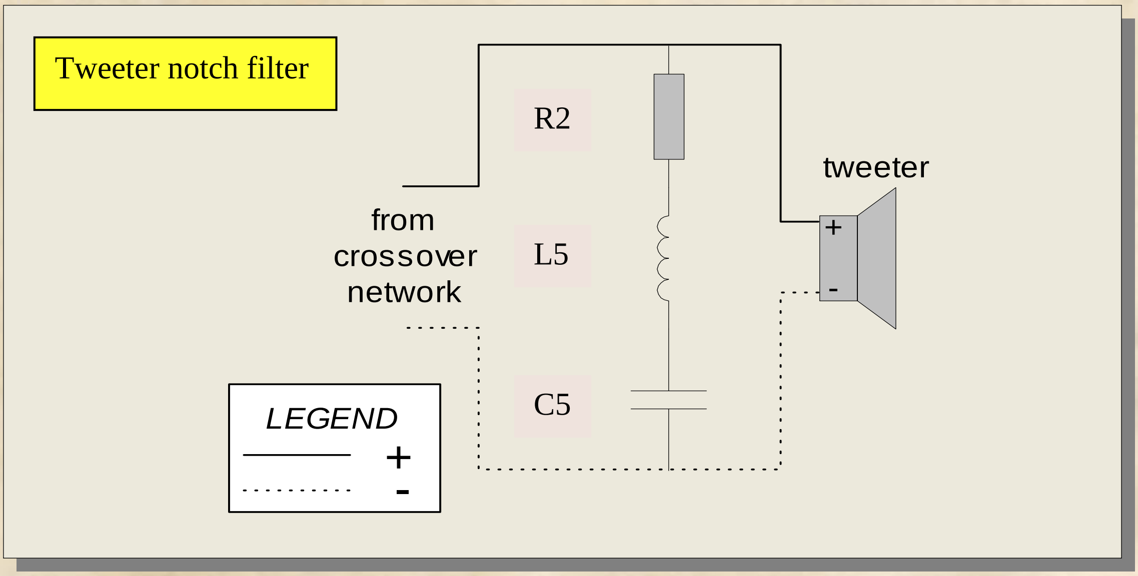


Fig. 27

Loudspeaker Phasing

If you have been careful in your wiring up of the networks and have connected your speaker cables with the correct **polarity**, then you won't have any phasing problems. This has nothing to do with phase distortion and is when one speaker is operating opposite to that of the other one, causing a cancelling effect, with a resultant drop in output. To test for this play a piece of music with a prominent bass drum or similar effect and feel if, when the bass drum is hit, the cones on both speakers move outwards at the same time. If you have a **sound level meter**, all you do is inject pink noise into the amp (usually found on a test cd or from a pink noise generator), set a relatively high volume to get a good reading on the meter and then reverse the connections of one speaker and see if the reading increases or decreases. If the reading is now lower, the speakers are out of phase, therefore changing the leads back will cause the reading to increase again so putting the speakers back in phase. (The sound cancels out when they out of phase).

Mid Notch Calculation Chart.

Parameters: F_n = …338...Hz

R3 = ….**7.2**…..Ω   L6 = …**3.26**...mH   C6 = …**68**…...µF

$$C_{ideal} = \frac{1}{2 \times \pi \times R_e \times F_n} \times 10^6 = \frac{10^6}{6.28 \times 7.2 \times 338} = ...\mathbf{65.40}......uF.$$

$$L_6 = \frac{1}{C_6 \times (2 \times \pi \times F_n)^2} \times 10^3 = \frac{10^3}{68 \times 10^{-6}(6.28 \times 338)^2} = ...\mathbf{3.26}......mH.$$

$$R_3 = R_e = ...\mathbf{7.2}...ohms.$$

F_n is the frequency of the notch you want to control and is usually equal to F_s.
Calculate C_{ideal} , then choose the nearest standard value capacitor for C_n to enable a small enough coil to be wound (<6mH).

Fig. 28

5.

Measuring the F_b of a Ported Speaker System

Carry out an impedance test of your enclosure and find the two peaks associated with a ported enclosure by sweeping across the 10 - 150 Hz range and note them as F_{high} and F_{low}. Now blank the port with an airtight seal (a piece of wood clamped down tight over the port) essentially converting it into an infinite baffle box (use a rubber gasket if necessary) and do an impedance sweep to find the single impedance peak associated with a sealed box and note it as F_c. It is usually the first and largest peak found. If the enclosure has a passive radiator fitted, it must be removed and the hole also sealed with an airtight seal when determining F_c.

Now use the formula:

$$F_B = \sqrt{(F_L^2 + F_H^2 - F_C^2)}$$

This should give you a very accurate measure of your actual box tuning frequency.

5.

Figure 29 shows a typical crossover parts list for a three-way system.

Crossover Parts List.

\+ = series connection. * = parallel connection.

crossover points = …500…&...4500…Hz.

Tweeter:

C1 = …2.35…µF = ….**2.2**…@…100….v ………..…@………v

C5 = ...7.89…µF = ….**47**….@….. 63…v + ..**10**…......@….. 63...v

R1 = …7.2…...Ω = ….**3.9**… + ….**3.3**…

R2 = …4.18…..Ω = ….**8.2**… * ….**8.2**…

L1 = …**0.522**…mH

L5 = …**0.71**…mH

Midrange:

C2 = ...25.65...…µF = …22…@…100....v * ..…2.2…@..100…v

C3 = …2.51……µF = …2.2…@…100...v ………….....@…....…v

C6 = …..22……µF = …22….@…100....v ……...…...@…......v

R3 = ….7.2…….Ω = ….**3.9**… + ….**3.3**…

L2 = …0.629..mH

L3 = …3.12…mH

L6 = …0.78…mH

Woofer:

C4 = …18.42..…µF = ….**47**…@…100...v + …..**33**..@…100v…v

C7 = ...7.89…µF = ….**33**…@.…63…v + …**10**..…@.…..63...v

L4 = …**5.50**…mH

R4 = …7.6…...Ω = …**15**… * …**15**…

Note: Use higher voltage caps on parallel connection.

Fig 29

5.

Summary.

1. The speaker cables must be able to carry the load without overheating.
2. Fit an “L” pad if the tweeter is too bright (loud).
3. Ensure that both speakers are connected with the correct polarity.
4. Do not place speakers directly on the floor, as a loss in response will occur.
5. Fit a notch filter if the midrange or tweeter resonate annoyingly.

Appendix A

Additional formulae.

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

$$r_o = \frac{Z_{fs}}{R_e} = \underline{\qquad} = \ldots\ldots\ldots\ldots\ldots$$ (see calculation chart for R_e , Z_{fs})

$$Q_{ms} = \frac{F_s \times \sqrt{r_o}}{(F_1 - F_2)} = \frac{\qquad \times \sqrt{\qquad}}{\qquad} = \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$V_{as} = 1.15 \times \left(\left(\frac{F_{box}}{F_s}\right)^2 - 1\right) \times V_{box} = 1.15 \times (\ldots\ldots\ldots - 1) \times \ldots\ldots\ldots$$

$= \ldots\ldots\ldots\ldots\ldots$litres (see Tupperware test for measuring F_{box})

Appendix B

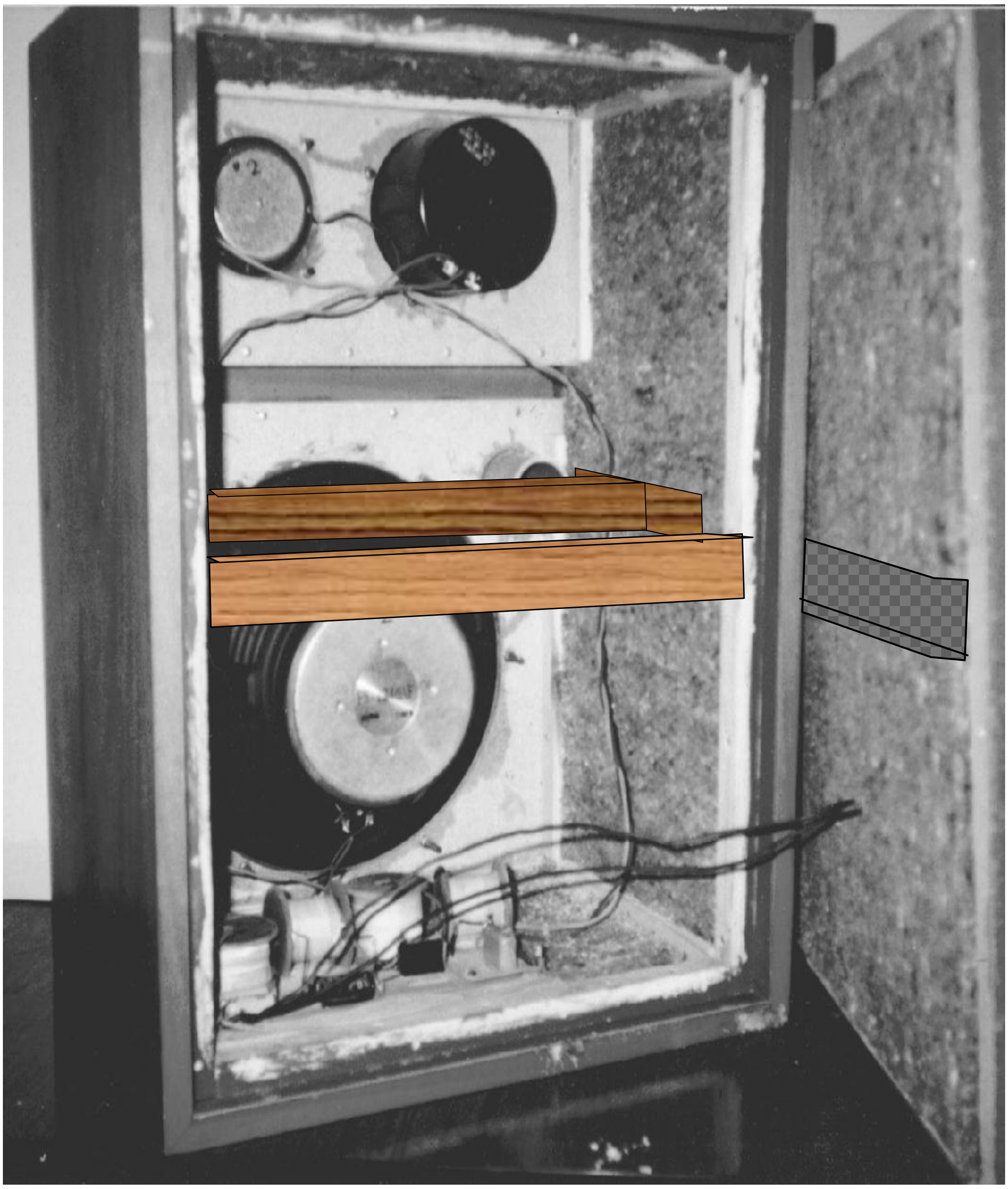


Fig 30

The light and dark wood pieces depicted above are the optional H-brace or the rear baffle centre brace. Note that if you fit a centre brace, you will have to cut the underfelt on the rear baffle to accommodate it, as it fits flush with the baffle. You can also drill holes across the width of the rear baffle so that it can be screwed to the brace for extra rigidity, but I have never felt the need for either of them (hence the crude drawing above). The H-brace is assembled by gluing and nailing/screwing the short end pieces to the longer cross brace (first do a dry fitting to see they it will fit across the width of the cabinet) and then glued in.

Appendix C

Loudspeakers Types

Woofers

Kevlar with rubber surround

Paper with reinforced cloth surround

Paper with foam surround

Fibre glass with rubber surround

Appendix C

Paper with cloth surround - guitar p/a speaker

Typical cut-away view

Appendix C

Midrange Speakers

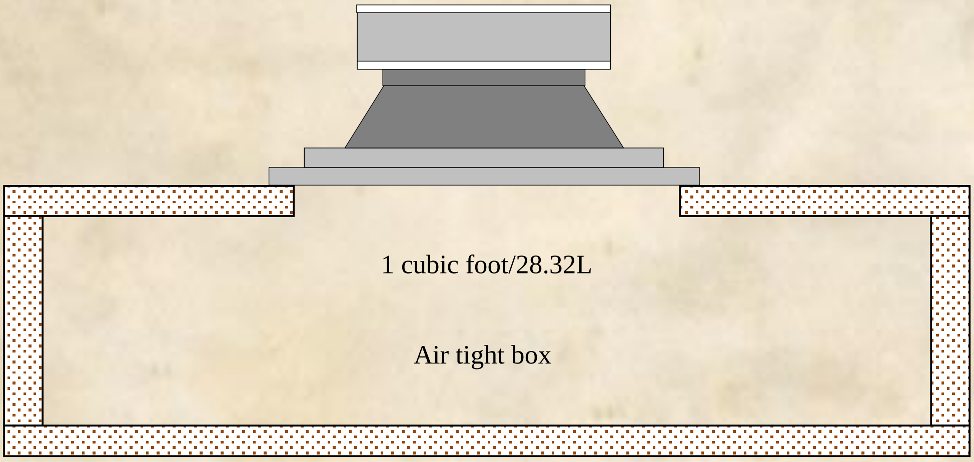
Typical midrange speakers in sealed tubes

Appendix C

Tweeters

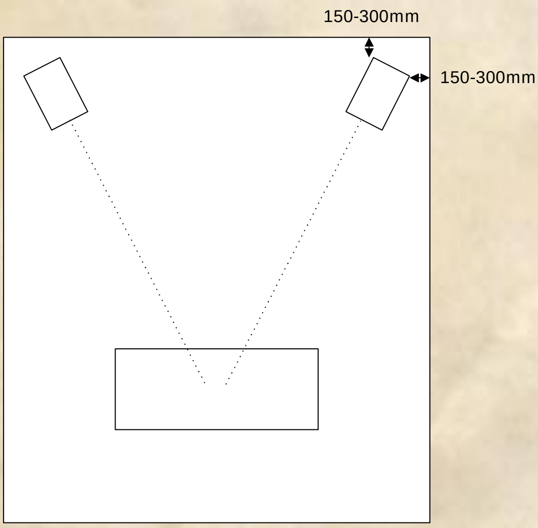
Typical soft dome tweeters

Appendix C



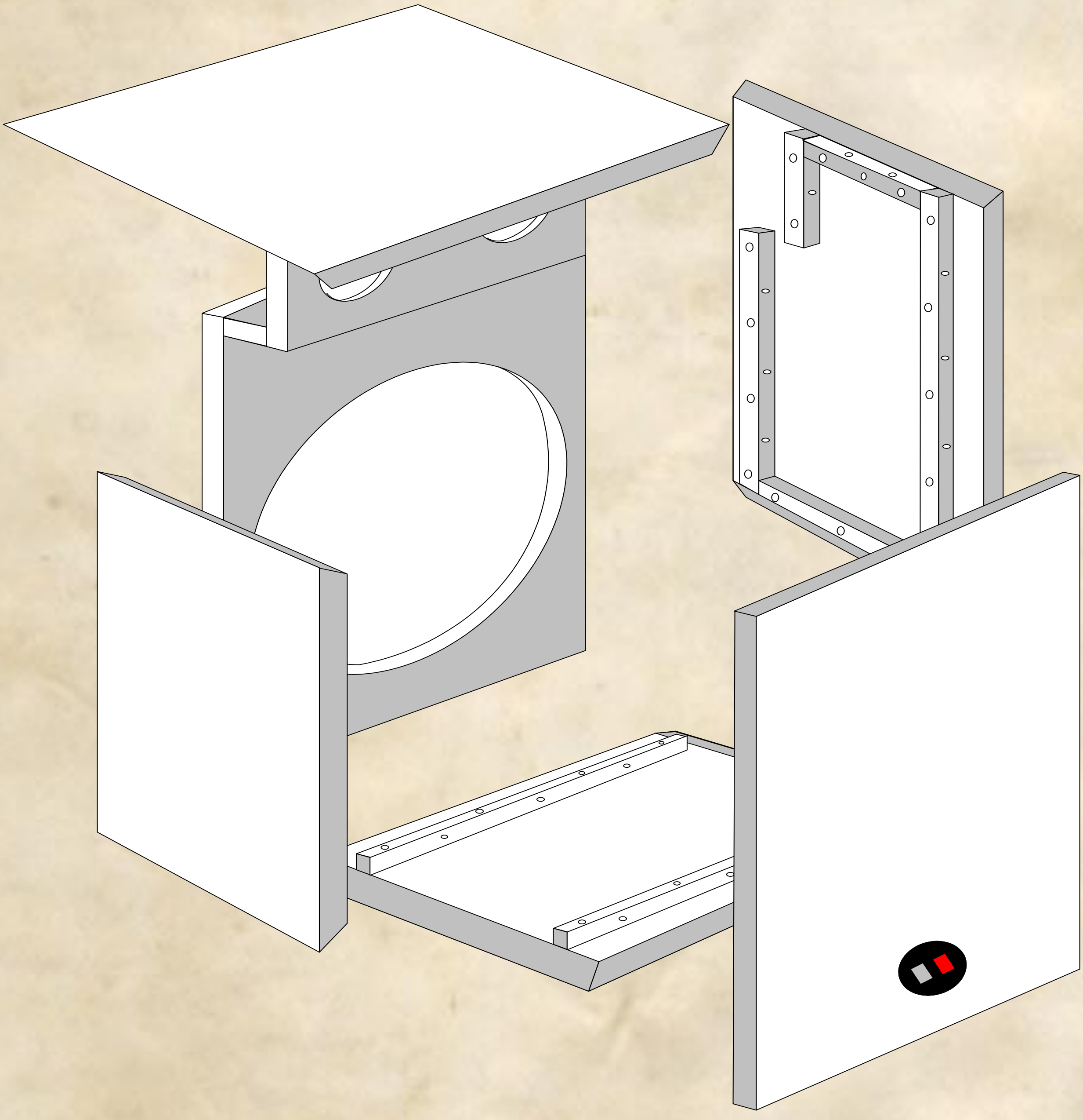
Loudspeaker test box

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.

Appendix C



Exploded view

Index.

R

S

T

U

V

W

Z

Note: Words that are cross-referenced with this index are highlighted in bold in the main text.

The Lost Art Of Loudspeaker Design Revision History

Rev1.0

Tidied up spreadsheet.

Rev1.1

Fixed L-pad formula in spreadsheet at cell D14 to read: =D12/B21.
Fixed spelling mistake at cell D8 ‘comment’ in spreadsheet .
Tidied some drawings, added some detail to 3-way schematic drawing, Zobel boxes.

Rev1.12

Corrected port length in Fig 12 drawing and recess formula in Fig 11.
Added this Revision page.

Rev1.13

Corrected filler dimension Fig. 15 and Fig. 17.
Corrected dimension in speaker placement drawing page 78.
Corrected this page at Rev1.0.

Rev1.14

Corrected ‘mid/tweeter recess’ formula in spreadsheet to include wood thickness at cell D40 in Box Sizes page: =I28-(I27+I30)+I23

Rev1.15

Added chapter on determining the frequency of the tuned cabinet.

Rev1.16

Changed Z’to Zf3 on charts. Fixed tweeter notch calculation chart to reflect the correct part numbering. Fixed mid notch figures.

Rev1.17

Fixed efficiency formula – correct multiplying factor 10^{-8}. Changed Qts formula to more commonly used one.