UNIVERSITY OF NAIROBI

DESIGN OF SPEAKER CABINETS

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BY: MURUNGA MUCHIKA ALBERT

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SUPERVISOR: MR L S OGABA

EXAMINER: MR DHARMADHIKARY

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DEDICATION

Specially dedicated to my Mum, my Dad and my Siblings.

“You are the people I love most”!
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In the course of research, preparation and completion of this report and especially the project itself, I have received help and advice from several people to whom I am greatly indebted.

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Finally yet importantly, I thank the Almighty God for the life, health and hope he has always given to me.
ABSTRACT

It is common all over the world that people like music and by extend good music. Therefore there is a very big advancement in developing and designing music systems. One of the most important components is the speaker cabinet, which other than housing the speaker; it is used to remove the waves emanating from back of the speaker. If these waves are not checked they interfere with waves from front of speaker.

But many times, due to poverty and ignorance people design, buy and or use any speaker cabinet for any speaker drive without doing any research or analysis and they end up getting an output much less than what is worth their money.

This project presents the study, design, and analysis of a simple, professional, inexpensive, optimum, and efficient speaker cabinet. In the study, different speakers in the market were studied and tested through simulation to determine their characteristics.

The relationship between speaker cabinet volume and the input electrical power was developed and used to design and analyze the speaker cabinet. Through analysis, the relationship was proved to be true and then used in the design of the speaker cabinet.

Lastly, a test of cabinet volumes deviating from the optimum volume was done and it proved that their frequency response and perfection was short of that of the optimum volume designed. The tests for restricted and relaxed volumes were done through simulation.
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INTRODUCTION

1.1 What is a speaker cabinet

This is a rigid enclosure of the speaker drive units and the crossover; it provides an appropriate acoustic loading for the drive units to obtain a good frequency response. This is achieved through the cabinet or the speaker enclosure trapping unwanted sound emanating from the back of the driver and adding acoustic resistance so that the driver can work more efficiently at low frequency.

1.2 Classification of speaker cabinets

Speaker cabinets are classified into two major groups; that is closed cabinets and vented or reflex cabinet. Closed cabinets are completely sealed box with only one chamber and no vents or passive radiators. Its simple to construct and is generally smaller.

Vented cabinet includes a single chamber with one or more openings that allows air to flow in and out of the box. These openings are called vents and they are modest in size, compared to the overall size of the box, so that they do not affect the ability of box to trap the unwanted sound waves that emanate from the rear of the woofer. These unwanted waves affect the compliance of the air inside the box.

1.3 Recognition of the previous work done on cabinet designs

So far, much has been done in the design of speaker cabinets. The big speaker manufacturing companies such as Eminence, Sony, Pioneer and even individuals for example WinISD beta have developed software to design and analyze speaker cabinets. The only setback being that nobody can access their codes or even the formulas used. In addition, most of this software is designed to work on only the products (design of cabinets for their
drivers or speakers) they manufacture and this makes it harder for anyone to use them for any other drive.

This being the case, there is a necessity of coming up with simple yet versatile formulas and relationships that can be used by anyone freely to design speaker cabinet for any driver of his/her choice. This therefore leads to the objective of the project.

1.4 Project objectives;

1. To study the existing speaker systems in the market and establish the following;
   - Power of speaker drives (woofers) RMS and PMPO
   - Internal volume of cabinet for speaker system.

2. To develop a relationship between input electrical power into the speaker drives (woofers) and the internal volume of the cabinet.

3. To build three cabinets of the following specifications and compare their performance:
   - Stiff box (approximately 70.7% of Normal volume).
   - Normal box
   - Oversize box (approximately 141% of Normal box)

1.5 The project structure

This project is divided into several chapters, which can be analyzed as follows:

- **Chapter 1**
  It involves the introduction and the basic definition of the project title, the problem statement, the project objectives and the project structure.

- **Chapter 2**
This chapter carries the background information and the theory behind the project. Detailed definition and explanation of the components of the speaker system are presented and this makes it easier to understand the design of the project.

- **Chapter 3**

This chapter deals with the real design of the speaker system. Design equation for the cabinet is derived and through simulation tools, the equation is proved. A speaker (woofer) is chosen and through a simulator, its frequency response is analyzed through different cabinet volumes. A table of comparison is made and conclusion drawn. The crossover design is also presented in this chapter and analyzed to develop the values of crossover components and their power ratings.

- **Chapter 4**

In this chapter, the experimental results were recorded and analyzed. A comparison between the simulated, expected and experimental results are presented in this chapter.

- **Chapter 5**

This chapter consists of the conclusion of the project report, including brief explanation of what was achieved in the project. There is a presentation of further work to be done in this project.

- **References**

This part of the project consists of the list of the books and sources where materials used in the writing and implementation of this project was found.

- **Appendix**

A drawing of the cabinet is shown with the dimensions. Some definitions are also given.
CHAPTER 2

THEORY AND BACKGROUND

2.1 Speaker system
A loudspeaker, here referred as a speaker system is an electro acoustic system, which combines
the characteristics of the loudspeaker (or transducer) itself and the cabinet in which it is mounted.
Most of the work involved in building a good sounding speaker cabinet involves trading off
various parameters of a desired speaker drive performance within the limits of acceptable box
size, low-end frequency response, maximum acoustic output (perceived loudness) and efficiency.

Speaker drives should technically exhibit a flat response over a wide range of frequency; exhibit
an even and a smooth directional pattern for the frequencies in a reasonably large listening room.

A single speaker drive can never fulfill this; the modern loudspeaker is a rather a complex
system consisting of a set of dynamic speaker drive units, crossover networks and enclosure.

The High-fidelity loudspeaker comprises of three fundamental parts, each having
different objectives;

1. Speaker drive units – provide acoustic energy; that is large membrane for low
   frequency and small membranes for the high frequency.
2. Cross-over network – directs the part of the signal, with energy in a certain frequency
   band, to the appropriate drive unit.
3. Enclosure - provides a dynamically rigid structural support for the drive units and to
   provide the appropriate acoustic loading for the drive units; to obtain a good
   frequency response.
THE ELECTRIC CIRCUIT OF THE SYSTEM

Figure 2.0: Equivalent circuit diagram of the speaker system.

\[ R_A = \text{Amp output resistance} \]
\[ R_C = \text{Speaker cable resistance} \]
\[ R_{\times O} = \text{Crossover inductor resistance} \]
2.2 SPEAKER DRIVES

There are four classifications of speaker drives depending on the band of frequency within which they operate;

- Sub-woofer → very low frequency
- Woofers → low frequency
- Mid-range (squawkers) → mid band frequency
- Tweeters → high frequencies.

THE DIAGRAM OF THE SPEAKER DRIVER (WOOFER)

![Diagram of a driver (woofer)](image)

*Figure 1.1a: diagram of a driver (woofer)*
THE SPEAKER SYSTEM CAN BE SHOWN AS BELOW

Figure 2.1b: diagram of a driver (woofer)

Figure 2.2 the three drivers built as a single unit, and their frequency response
2.3 ENCLOSURES (SPEAKER CABINET)

The purpose of the speaker enclosure or box is to trap unwanted sound emanating from the back of the driver and to add acoustic resistance so that the driver can work more efficiently at low frequencies.

An ideal enclosure would be infinitely rigid. It would secure the drive units in a fixed position, and be acoustically transparent. However, real enclosures are elastic structures having specific dynamic characteristic. The reaction of the drive units, and the sound pressure, ‘excite’ the enclosure, causing it to vibrate.

The structural vibrations are transmitted to the air, contributing to the total sound image. Panel vibrations can produce a significant contribution to sound, being of the same order of magnitude as the direct drive-unit sound, at panel resonance frequencies. The panel sound is generally uncontrolled, interfering destructively with the direct sound, causing magnitude and phase errors in frequency response, and causing the radiation pattern to deteriorate.

2.3.1 Types of enclosures

1. Closed box enclosure

A "closed box" is a completely sealed box with only one chamber and no vents or passive radiators. It is the simplest type of box to construct and is generally smaller than other types of box. It is used for giving woofer parameter variations, making it a good choice when tight woofer parameter tolerances cannot be maintained. Closed boxes have gradual 2nd order or 12 dB/octave low-frequency cutoff rates.

2 Reflex enclosures or Vented Boxes

A "vented box" has a single chamber, with one or more openings, that allow air to flow in and out of the box. These openings are called "vents" and they are modest in size, compared to the
overall size of the box, so that they do not affect the box's ability to trap the unwanted sound waves that emanate from the rear of the woofer. Therefore, they will not affect the compliance of the air inside the box.

A vent is constructed with a tube (also called a "duct") that is mounted through a round hole in the wall of the box. The vent tube dimensions are calculated to cause the box to resonate at a desired frequency ($F_b$) and the vent creates its own sound waves at this frequency. The box resonant frequency is often set close to the free air resonance of the driver ($F_s$). Two major advantages of a vented box are: (i) its ability to extend the bass response. (ii) Its rapid 4th order or 24 dB/octave low-frequency cutoff rates.

A vented box can have a phase shift as high as $360^\circ$—but $270^\circ$ is more typical at the low frequency limit of its response. This means that the low frequency sound waves created by the speaker drive may lag by as much as one full wavelength but usually by no more than three-quarters of a wavelength. With double the phase shift of a closed box, vented boxes reproduce low-frequency transient signals less accurately than a comparable closed box.

**Comparison between closed box and vented box (enclosure)**

**Advantages of sealed box**

1. Easy to built.
2. Can handle better ultra low ($<30$ Hz) frequency without destroying the woofer.
3. Generally the most accurate box in the mid-bass frequency.

**Disadvantages**

1. Low bass response.
2. Lower efficiency than that of vented box.

**Advantages of vented box**

1. Better low frequency response.
2. Better efficiency.

Disadvantages

1. More difficult to design
2. Frequency below cut off frequency can cause the woofer to be damaged.

2.3.2 CABINET VIBRATIONS AND MEASURES TAKEN AGAINST

Speaker cabinets are expected to be stiff, but, practically they are elastic therefore they vibrate when they absorb energy from the speaker drives. This makes it necessary to remove the vibrations. Measures against vibrations can be achieved by increasing the mass and/or stiffness of the panel to remove resonance frequencies or decrease the compliance. The following is done in order to achieve this:

Loudspeaker Dampening
In every loudspeaker; sound wave are produced at the rear of the speaker drives(woofer). Those waves will have their energy absorbed into the enclosure causing the enclosure to resonate (vibrate). This interaction between the standing sound waves and the enclosure is what causes the audible coloration and smearing of the loudspeaker's sound. In extreme conditions where the enclosure has no dampening materials, the energy from the standing waves can approach the output of the drive unit itself. To control these waves, we dissipate their energy through frictional losses with any material that offers high resistance to the sound waves such as a damping sheet or acoustical dampening fiberfill.
Cabinet shape
The cabinet shape also is also a factor in limiting enclosure resonance. A cube is the absolute worse shape that a loudspeaker could be; due to the standing waves produced inside the enclosure. In general the Golden Rule Ratio of (Height 2.618: Width 1.618: Depth 1.000) is used. This ratio will minimize these standing waves and the resulting enclosure resonance and distortion.

Speaker Box Enclosure Mass Loading
Adding weight such as dry sand or lead shot into a special compartment at the base of the enclosure will benefit the loudspeaker by increasing its effective mass. By adding mass to the loudspeaker structure, it will act as an efficient absorber of vibration energy. The heavier an object is the more energy it takes to make it vibrate; so weight is a resonance dampener.

Speaker Box Enclosure Material
Medium Density Fiberboard (MDF) or Medium Density Overlay (MDO) board is the product of choice. This is due to its relative low cost, and because it is strong. Higher quality plywood that has no voids in the laminations is acceptable. Three quarters of an inch is the minimum board thickness that should ever be used because a strong and stiff enclosure is needed to minimize enclosure resonance. Chipboard has the same characteristics of the MDF only that it needs some external finish.

Speaker Drives Alignment within the Box Enclosure
The tweeter, midrange and the woofer should be kept in a straight vertical line with one another; this is done to keep the sounds in-phase with the listener’s ear. The woofer sits nearer to the floor and the tweeter should be near ear level with the midrange in between the two. All drivers are mounted close together; the sound quality is improved due to less phase shifting and better imaging.
Make the Speaker Box Enclosure Air Tight
The enclosure is made airtight (except for the port). Leaks will show themselves as unwanted air noises and in more extreme cases, the leaks could effect the proper operation of the speaker drives and change the port frequency of base reflex loudspeakers.

2.4 CROSSOVERS

The crossover network is responsible for dividing the sound bandwidth into specific frequencies and sending them to the proper speaker drive component. This is done by the use of inductors, capacitors and resistors for the case of passive crossovers. Coils filter out higher frequencies and capacitors filter out the lower frequencies.

No one single speaker drive is capable of reproducing the entire audio sound bandwidth faithfully. Because of this, the task is divided among two or more speaker drives to get better sound quality. A typical three-way loudspeaker (speaker system) consists of a woofer, a midrange and a tweeter. Each one of these components is designed to reproduce a certain bandwidth of the sound spectrum. The woofer typically reproduces all the sounds under around 500Hz, the tweeter may take all the frequencies above 6000Hz and the midrange reproduces everything in between. By dividing the frequencies into three different speaker components, the overall sound quality is dramatically improved over that of a single component loudspeaker (speaker systems).

CLASSIFICATION OF CROSSOVERS

Crossovers can be classified in the following using these major categories.

1. The number of speaker drives being driven by the crossover.
2. The rate at which the unwanted frequencies are attenuated.
2.4.1 According to number of speaker drives driven by the crossover.

a. 2-way crossovers

This crossover divides the frequencies only in two levels that are high frequency for the tweeter and low frequency for the woofer. This is shown in the diagram below.

![2-way Crossover Diagram](image)

*Figure 2.3: 2-way crossover*

b. 3-way crossover

In this configuration, the frequency components are divided into three, which an extra speaker drive (midrange) included.

The midrange driver gets the frequencies in the middle of the bandwidth; for this, a Band-Pass filter is used. A Band-Pass filter uses both a capacitor and a coil (inductor) in series for a 1\textsuperscript{st} order crossover. The capacitor blocks the lower frequencies and the coil block the higher frequencies leaving only the midrange frequencies to pass into the midrange speaker drive.

![3-way Crossover Diagram](image)

*Figure 2.4: 3-way crossover*
Below is a more realistic crossover slope for a passive crossover network. It is evident that the frequencies around the crossover point (1800 Hz) are being shared between two separate drivers. The big problem this has as compared to the Brick Wall crossover is that now two separate speaker drives often of different size, shape and material are reproducing the same frequencies. Those frequencies will interact with one another causing distortion that affects the loudspeakers accuracy; this is referred to as Wave Interference.

Passive networks use capacitors and inductors, which work by gradually removing (attenuated) the unwanted frequencies. How fast these unwanted frequencies are removed (attenuated) by the filter depend upon the design of the crossover. First, order ones are the simplest, but they are also
the slowest acting. As the order of the crossover is increased, there is increase in the ratio (speed) at which the unwanted frequencies are removed and lessen the wave interference.

Classification according to rate of attenuation of unwanted frequencies

a. First-order
These crossovers have a 6db/octave attenuation rate for the unwanted frequencies. First-order crossovers are often chosen over higher order designs because of their relative simplicity and response, which is predictable because first-order crossovers are, less affected by impedance variations than the other higher-order crossovers. Due to the slow acting speed, usage in a three-way system is not recommended.

High-Pass Filter (first order) - The capacitive reactance causes an increase of ‘resistance’ at lower frequencies. This increase of resistance to lower frequencies filters out the lower frequency signal and allows the higher frequency ones to pass through. This is used for tweeters.

![Figure 2.8: A high-pass filter for the tweeter.](image)

Low-Pass Filter (first order) - The inductive reactance causes increases of resistance as the frequencies rise. This increase of ‘resistance’ at higher frequencies filters out the high frequency signal and allows the low frequency signal to pass. This is used for woofers.

![Figure 2.9: A low-pass filter for the woofer](image)
Band-Pass Filter (first order) - The coil and capacitor filters out both the low and high frequency signals and allowing only the mid range frequency to pass. It is used for midrange speaker drives.

Crossover networks work in a gradual way, they work by adding in frequency related resistances that are used to filter out certain frequencies. First-order 6 db per octave crossovers will give about a 75% reduction in power per octave (100Hz) and about a 94% reduction at 2 octaves. Therefore, at a crossover point of 400 Hz, the frequencies at 500Hz are still at 25% of full power and at 600Hz, it is at 6% of full power. If a faster acting crossover is needed then you will need to build a second or Third-order filter. This is important when it comes to tweeters because they are much more sensitive and are more likely to fail if subjected to frequencies below what they were designed to handle.

b. Second-order
Second-order filters act twice as fast as a first order filter. They attenuate the unwanted frequency at 12db /octave. The first-order reduced the power by only 75% at one octave above the crossover frequency; the second order reduces the power by 93%.

On second-order crossovers (two-way), the phase shift is 180 degrees (reversed polarity) and is known as phase reversal. In a two-way system, the tweeter and woofer are firing out of phase with one another. This is easily corrected by reversing the wires on the tweeter. For a three-way second order system, the midrange wires are usually wired in reversed leaving it "out of phase" (but not really) with the tweeter and midrange. Doing this allows all the drivers to operate in phase with one another.

Special Filters

Zobel Filter - Is used to "control" the variances in the speaker drive’s impedance produced in the relative larger voice coils of a woofer and some midrange drivers. Tweeters may also benefit form a zobel filter; but if your tweeter has Ferro fluid in it you won't need a zobel filter.
**L-pad** - In general, as a speaker drive becomes larger, it usually becomes more inefficient. Tweeters tend to be very efficient, midrange speakers are less efficient than tweeters and woofers tend to be the least efficient. The reason for this is that a woofer has to move a lot of air, for every octave drop in the audio spectrum the driver has to be capable of moving 4 times more air to keep the same output level (loudness). Tweeters do not have to move much air so efficiency is easily maintained. Woofers that are capable of 19 Hz and below are very inefficient compared to woofers that only go to 35 Hz.

L-pads are often used on both the midrange and woofer to attenuate (reduce) their power level (loudness) to match the woofers efficiency (loudness). L-pads are variable control and thus easily adjusted after it is installed.

**Attenuation Circuit** - Also used to match the output levels of different drivers but not as easily adjustable as the L-pad. Tweeters are generally more efficient (higher sensitivity) than woofers, this could result in an overly loud tweeter as compared to the woofer. This circuit will attenuate (reduce) the tweeter output. Attenuating the tweeter can simply be done by adding only a resistor in series with the tweeter. Problem is that you just added more load to your amplifier, using the two resistors as in attenuation circuit would not increase the circuit’s impedance, only the impedance going to the tweeter.
CHAPTER THREE

DESIGN AND ANALYSIS OF SPEAKER CABINET

3.1 DESIGN CONSIDERATIONS

a) **Bandwidth or frequency response** is a measure of the highest and lowest frequencies that can faithfully be reproduced a speaker system. A frequency response curve is a graph showing the acoustic energy produced by the speaker over its entire bandwidth. The response curve shows how linear amplitude is through the bandwidth, and is a more important indicator of quality than simply knowing the upper and lower cut-off frequencies.

A frequency response curve should be as close to linear as possible. If a speaker system has large peaks and dips in its response curve, then certain frequencies presented to the system will be louder than others, even when presented with equal amplitudes. Therefore, a broad and linear response curve is unquestionably the most important aspect of system design.

b) **Distortion** is nearly as important as bandwidth linearity. Distortion is a measurement of inaccuracy exhibited when a signal of single frequency is presented. Usually measured as a percentage, it gives an indication of how much of a signal heard is the result of speaker imperfections.

Several things can cause distortion, and most can be avoided through careful speaker system design. Most speaker system elements are made using an electromagnetic or electrostatic linear motor assembly connected to a cone. In this arrangement, the motor should be carefully designed to ensure that it moves in a controlled fashion, and that it moves exactly with the signal presented to it. The cone attached to the motor may not be rigid enough and may begin to vibrate at harmonic frequencies when presented with certain signals. Further, the mounting of the cone requires a suspension, which may prevent the cone from free movement and may cause the cone to twist or limit its motion more in one direction than the other. Therefore, even though the motor assembly is simple, it is important to engineer and build the motors carefully, and to choose only those that are of high quality.
c) **Dynamic range** is a combination of two parameters – efficiency and power handling. A broad dynamic range is important because it describes the difference between the lowest and highest levels of acoustic amplitude that the loudspeaker can reproduce. Having a speaker drive that can handle an enormous amount of power is unimpressive if its efficiency is so low. That high power levels cause it to provide a relatively low volume of sound.

d) **Efficiency** is rated in decibels – over threshold of hearing – with one watt of electrical energy. Specifically, the amount of energy required to even hear a sound of 0.00002 Newton/sq. meter, and is defined as 0db. Further, the accepted way to measure efficiency is relative to this reference value, when providing a signal of 1 watt to a speaker and measuring its acoustic output at 1 meter’s distance.

e) **Power handling** is a measure of how much power can be presented to a speaker drive without causing it to be damaged. Often times, cone travel is impaired by the speaker drives suspension at power levels much lower than its rated maximum, so that fact must be taken into consideration. It is generally safest to assume that distortion rises dramatically between 50% and 70% of a speaker drive’s maximum rated power handling capacity.

Power handling is measured in watts, and because of the transient nature of audio signals an averaged measurement of rating known as R.M.S. is commonly used. R.M.S. stands for Root-Mean-Squared, and when comparing specifications it is safest to use this figure.

f) **Phase shifts** are differences in time between two components of an audio signal. For example, when a snare drum is played, two distinct sound components are created at the same time – a low frequency sound that is the result of the resonation of the drum and a higher frequency sound that is caused by the impact of the drumhead and the vibrations of the snares. If the two signals are separated and sent to different speaker systems elements, and if one of the elements is much closer to the listener than the other, then one component of the sound will reach the listener sooner than the other.
Phase shifts are also introduced to a small degree by crossover components and by the electrical characteristic of the driver motors themselves. However, these shifts are much less than one cycle and are negligible. The only problem that can arise from these small phase shifts is the possibility of two speaker drives receiving a portion of a signal, and then being shifted near 180 degrees so that the sound output of the individual drivers partially cancels or modifies the other.

g) Reflections are caused by interference from objects away from the source of the projected sound. These objects can be outside the loudspeaker enclosure – in the listening environment - or they may be a result of the loudspeaker itself.

h) Impedance is a measure of how much difficulty electrical energy has when passing through a conductor. It is important that the impedance of a loudspeaker be matched with its amplifier. Too high impedance will not allow the amplifier to transfer energy into them. Too low impedance will draw too much power from an amplifier without properly transferring the electrical signal, which will cause the amplifier to prematurely clip and create harmonic distortion that is annoying and damaging.

It is important to choose components of the same impedance except in a few special cases. Speaker drivers connected in parallel increase efficiency but not power handling and drivers in series increase power handling but not efficiency. A loudspeaker can be designed with two midrange drivers connected in series to double power handling capacity of the midrange system. Perhaps two low frequency speaker drives are connected in parallel to increase bass efficiency by 3db.

Speaker system design should start with the low end of the audio spectrum. First, a woofer should be chosen which exhibits a flat response curve and a low cutoff frequency. The factors for consideration should be the required low frequency cutoff point and power handling capacity. No consideration should be made for woofers with non-linear response curves or high total harmonic distortion levels – only the components tested and shown to have the most superior performance levels in frequency linearity and distortion should be used.
3.2 SPEAKER DRIVE PARAMETERS USED IN DESIGN AND ANALYSIS

These parameters are also known as Thiele/Small Parameters, which were designed by Thiele of Australian Broadcasting Corporation and Small from University of Sydney.

Constant

\[ \alpha' = \left( \frac{Q_{te}}{Q_{ts}} \right)^2 - 1 \]

Speaker system total Q at \( f_c \) - it is the system quality factor at system resonance frequency.

\[ Q_{te} = (\alpha' + 1)^{\frac{1}{2}} Q_{ts} \]

Speaker system total Q at \( f_s \) - it is the system quality factor at speaker system resonance frequency.

\[ Q_{ts} = \frac{Q_{te}}{(\alpha' + 1)^{\frac{1}{2}}} \]

Efficiency bandwidth product

\[ EBP = \frac{f_s}{Q_{es}} \]

Speaker system resonance frequency - it is the resonance frequency of the speaker system.

\[ f_s = EBP \times Q_{es} \]

Speaker drives electrical \( Q_{es} \) - it the electrical quality factor of the system.

\[ Q_{es} = \frac{f_s}{EBP} \]

System resonance frequency - it is the systems resonance frequency.

\[ f_e = \frac{Q_{te} \times f_s}{Q_{ts}} \]

Speaker system total Q at \( f_e \) - it the total speaker system quality factor at systems resonance frequency.

\[ Q_{te} = \frac{f_e \times Q_{ts}}{f_s} \]
Speaker resonance frequency

\[ f_s = \frac{f_c \times Q_{ts}}{Q_{ce}} \]

Speaker total Q at \( f_s \)

\[ Q_{ts} = \frac{Q_{ce} \times f_s}{f_c} \]

Minus three decibel, half power frequency- it is the cut off frequency of the speaker.

\[ f_3 = \left[ \left( \frac{1}{Q_{ce}^2} - 2 \right) + \sqrt{\left( \frac{1}{Q_{ce}^2} - 2 \right)^2 + 4} \right] \times f_c \]

System resonance frequency

\[ f_c = \frac{f_3}{\left[ \left( \frac{1}{Q_{ce}^2} - 2 \right) + \sqrt{\left( \frac{1}{Q_{ce}^2} - 2 \right)^2 + 4} \right] \times f_c} \]

Net internal box volume –it the net internal volume of the cabinet.

\[ V_b = \frac{V_{as}}{\alpha} \]

Air volume with same acoustic compliance as the speaker suspension.

\[ V_{as} = V_b \times \alpha \]

Constant

\[ \alpha = \frac{V_{as}}{V_b} \]

Free air reference efficiency –it is free air efficiency of the system.

\[ \eta_o = \frac{2.7 \times 10^{-8} f_s^3 V_{as}}{Q_{ce}} \]
Speaker system resonance frequency

\[ f_s = \left[ \frac{\eta_o Q_{es}}{2.70 \times 10^{-8} V_{ax}} \right]^{1/3} \]

Air volume with same acoustic compliance as the speaker suspension

\[ V_{ax} = \frac{\eta_o Q_{es}}{2.70 \times 10^{-8} f_s^3} \]

Speaker drive electrical Q

\[ Q_{es} = \frac{2.7 \times 10^{-8} f_s^3 V_{ax}}{\eta_o} \]

Sound pressure level

\[ SPL = 112 + 10 \log_{10} \eta_o \]

Free air reference efficiency

\[ \eta_o = 10^{\frac{SPL-112}{10}} \]

Maximum air volume displaced by cone excursion

\[ V_d = S_d \times X_{max} \]

Cone effective radiation area

\[ S_d = \frac{V_d}{X_{max}} \]

Cone peak linear displacement

\[ X_{max} = \frac{V_d}{S_d} \]

Cone effective radiation area

\[ S_d = \frac{\pi D^2}{4} \]
Cone diameter plus one third of surround

\[ D = \sqrt{\frac{4S_d}{\pi}} \]

\( K_1 \) constant

\[ K_1 = \frac{4\pi^3 R_o f_c^4 V_d^2}{c} \]

Air density

\[ R_o = \frac{K_1 c}{4\pi^3 f_c^4 V_d^2} \]

System resonance frequency

\[ f_c = \left( \frac{K_1 c}{4\pi^3 R_o f_c^4} \right)^{\frac{1}{4}} \]

Maximum air volume displaced by cone excursion

\[ V_d = \left( \frac{K_1 c}{4\pi^3 R_o f_c^4} \right)^{\frac{1}{2}} \]

Sound speed in air

\[ c = \frac{4\pi^3 R_o f_c^4 V_d^2}{K_1} \]

\( K_2 \) constant

\[ K_2 = 112 + 10 \log_{10} K_1 \]

\( K_1 \) constant

\[ K_1 = 10^{\frac{K_2 - 112}{10}} \]
\( A_{\text{max}} \) constant

\[
\text{when } Q_x > \sqrt{0.5}, \quad A_{\text{max}} = \frac{Q_x^2}{\sqrt{Q_x^2 - 0.25}}
\]

\( else, \ A_{\text{max}} = 1 \)

Maximum displacement limited linear power output

\[
P_{ar} = \frac{K_1}{A_{\text{max}}}
\]

\( K_1 \) constant

\[
K_1 = P_{ar} A_{\text{max}}
\]

\( A_{\text{max}} \) constant

\[
A_{\text{max}} = \frac{K_1}{P_{ar}}
\]

Required electrical input to achieve \( P_{ar} \) - it is the RMS electrical power into the speaker drive.

\[
P_{er} = \frac{P_{ar}}{\eta_o}
\]

Maximum displacement limited linear power output – it is the acoustical out power.

\[
P_{ar} = P_{er} \eta_o
\]

Free air reference efficiency

\[
\eta_o = \frac{P_{ar}}{P_{er}}
\]

Peak sound pressure level

\[
SPL_{\text{peak}} = 112 + 10 \log_{10} P_{\text{max}}
\]

Maximum speaker power input

\[
P_{\text{max}} = 10^{\frac{SPL_{\text{peak}} - 112}{10}}
\]
CABINET DESIGN

3.3 THE DESIGN EQUATIONS

Developing the relationship between cabinet volume and input power to speaker drive.

Using Thiele/Small parameters (these equations are in the reference), the cabinet design equation was developed.

Expressing Electric input power into the speaker drive (woofer) as follows;

\[ P_{cr} = \frac{P_{ar}}{\eta_0} \]

And the cabinet volume as follows;

\[ V_b = \frac{V_{as}}{\alpha} \]

The constant is calculated using the equation below;

\[ \alpha = \left( \frac{Q_{ts}}{Q_{ts}} \right)^2 - 1 \]

Substituting efficiency, the power is expressed as below;

\[ P_{cr} = \frac{P_{ar}}{2.7 \times 10^{-3} \times f_s^3 \times V_{as}} \]

However, \( V_{as} \) is represented as follows;

\[ V_{as} = V_b \alpha \]
Substituting for $V_{as}$, we get;

$$P_{er} = \frac{P_{ar} \times Q_{es}}{2.7 \times 10^{-8} \times f_s^3 \times V_b \times \alpha}$$

Therefore, the cabinet volume is represented by;

$$V_b = \frac{P_{ar} \times Q_{es}}{2.7 \times 10^{-8} \times f_s^3 \times \alpha \times P_{er}};$$

Letting everything other than input electrical power into the speaker drive and cabinet volume as a constant $k$, we have:

$$V_b = \frac{K}{P_{er}}.$$

This was the desired relationship between input electric power to the speaker drive and the cabinet volume. This relation ship was proved by comparing its value and simulated value. It is also important to note that the value $k$ is specific for every woofer

### 3.3.1 APPLICATION AND PROOVING OF THE FORMULA

Consider a Seas H630 woofer with the following parameters,

- $P_{ar} = 60$ watts, $Q_{tc} = 0.71$, $Q_{es} = 0.38$, $f_s = 34$ Hz, $V_{as} = 45.1$, $Q_{es} = 0.46$. 

Then;

$$\eta_0 = \frac{2.7 \times 10^{-8} \times 45.1 \times 34^3}{0.46} = 0.1044$$
\[ \alpha = \left(\frac{0.71}{0.38}\right)^2 - 1 = 2.49 \]

\[ k = \frac{P_{ar}Q_{es}}{2.7 \times 10^{-8} \times f_s \times \alpha} = 1068.311 \]

\[ V_b = \frac{1068.311}{6.24} = 18.1 \text{ Litres} \]

The simulated volume using WinISD beta for the same speaker drive (woofer) is 18litres. This is the same using Eminence simulator. The table below shows simulation volume and volume from the derived formula for two woofers in the market with different parameters.

*Table 1 Comparison of simulated cabinet volumes and calculated volume*

<table>
<thead>
<tr>
<th>woofer model</th>
<th>rms power rating</th>
<th>simulated volume</th>
<th>Calculated volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>WinIsd</td>
<td>Eminence</td>
</tr>
<tr>
<td>Seas H630</td>
<td>60 watts</td>
<td>18 litres</td>
<td>18 litres</td>
</tr>
<tr>
<td>Eminence383</td>
<td>200 watts</td>
<td>420 litres</td>
<td>420 litres</td>
</tr>
<tr>
<td>Woofer used for design</td>
<td>50 watts</td>
<td>17.5 litres</td>
<td>17.5 litres</td>
</tr>
<tr>
<td>(Pioneer TX-120)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From the table it is evident that the derived formula is correct and can be used to calculate the cabinet volume given the inputs power and the Thiele/Small parameters.

For the designed system in this project (Pioneer TX-120) the parameters are \( P_{ar} = 50 \text{ watts}, Q_c = 0.71, Q_s = 0.58, f_s = 77.4 \text{ Hz}, V_{as} = 8.5 \text{ Litres}, Q_{es} = 0.36. \)

Using the above formula the cabinet volume was found to be 17.0litres.
3.4 THE DESIGN OF CROSSOVERS

3.4.1 The values of the components were calculated using these equations;

\[ L = \sqrt{2} \times \frac{Z_L}{2\pi f} \]
\[ C = \frac{1}{2\pi f \times Z_C \times \sqrt{2}} \]

Using these formulas as an example;

\[ L_1 = \left(\frac{2\pi f}{Z_1}\right)^{-1} \times \sqrt{2} \]
\[ C_1 = \frac{(Z_1 \times 2\pi f)^{-1}}{\sqrt{2}} \]

Where \( Z_1 \) is the speaker drive impedance; 4 ohms

At the 1000 Hz cut off frequency the values as shown below;

\[ C_{21} = 56.27 \mu F \]
\[ L_{21} = 1.801 mH \]

At 5000 Hz the calculated values are;

\[ C_{22} = 28.485 \mu F \]
\[ L_{22} = 0.900 mH \]

Where the first subscript indicate the second order and the second subscript indicate the cut off frequency that is the first cut off and the second cut off frequency. The circuit diagram in figure 14 was designed.
3.4.2 CALCULATING THE COMPONENT RATINGS OF THE CROSSOVER

Inductors and resistors are rated in watts, but capacitors are rated in volts. That is why it is important to know the voltage presented to the system. In addition, since the crossover components are dividing energies between components and themselves, calculations must be performed to know what the highest stresses are.

To calculate voltage, one must also know the current and impedance of the system. The given parameters are power and impedance of each component, so we must start by calculating system impedance using each individual component:

\[
Z_t = Z_1 + Z_2 + Z_3 \ldots \quad \text{(For series)}
\]

\[
Z_t = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} \ldots} \quad \text{(For parallel)}
\]

Where \( Z_t \) is total system impedance
$Z_1$ is impedance of series component 1

$Z_2$ is impedance of series component 2

$Z_3$ is impedance of series component 3

Most loudspeaker systems will have a combination of components, making a series-parallel network. Take for example, a simple system with one woofer using a crossover coil and one tweeter with a crossover capacitor. This configuration will have two series circuits connected in parallel with each other. Impedance can only be calculated at specific frequencies, and it is important to know impedance at two frequencies – each in the mid-band of a driver. These equations were used to calculate the ratings of the cross over components after knowing the input rms power, for this case the power was 30 watts.

\[ P = I^2Z, \quad P = \frac{E^2}{Z}, \quad P = EI, \quad E = \sqrt{PZ}, \quad E = \frac{P}{I}, \quad I = \frac{E}{Z}, \quad I = \sqrt{\frac{P}{Z}}, \quad I = \frac{P}{E}. \]

\[ Z = \frac{E}{I}, \quad Z = \frac{P}{Z^2}, \quad Z = \frac{E^2}{P}. \]

Using the above equations the ratings of each component were found by replacing each component with its impedance and calculating the system voltages and currents at each component level.
CHAPTER 4

ANALYSIS AND DISCUSSION OF SIMULATED AND EXPERIMENTAL RESULTS

4.1 EFFECTS OF CHANGING ENCLOSURE VOLUME WITH THE SAME INPUT ELECTRICAL POWER INTO A SPEAKER DRIVE (WOOFER).

Through simulation using WinISD the following results were obtained

4.1.1 WinISD test of Pioneer TX drive (woofer) in different cabinet volumes.

Pioneer TX –M120 (50watt)

Table 2 Effects of changing cabinet volumes for a 50 watts Pioneer TX-M120 woofer.

<table>
<thead>
<tr>
<th>Volume(liters)</th>
<th>Qtc</th>
<th>Lower cutoff frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>2.30</td>
<td>202.22</td>
</tr>
<tr>
<td>2.10</td>
<td>1.30</td>
<td>125.05</td>
</tr>
<tr>
<td>12.40(17.50 ÷√2)</td>
<td>0.75</td>
<td>94.56</td>
</tr>
<tr>
<td>17.50(optimum volume)</td>
<td>0.71</td>
<td>94.56</td>
</tr>
<tr>
<td>24.80(√2 × 17.50)</td>
<td>0.67</td>
<td>94.56</td>
</tr>
<tr>
<td>40.30</td>
<td>0.63</td>
<td>95.63</td>
</tr>
<tr>
<td>351.81</td>
<td>0.59</td>
<td>97.79</td>
</tr>
</tbody>
</table>
4.1.2 WinISD test of Orevox WP 4008 drive (woofer) in different cabinet volumes.

Table 3 Effects of changing cabinet volumes for a 20 watts Orevox Wp 4008 woofer.

<table>
<thead>
<tr>
<th>Volume(liters)</th>
<th>Qtc</th>
<th>Lower cutoff frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>1.04</td>
<td>75.62</td>
</tr>
<tr>
<td>7.0(9.9 ±√2)</td>
<td>0.73</td>
<td>66.87</td>
</tr>
<tr>
<td>9.9(optimum V)</td>
<td>0.71</td>
<td>66.87</td>
</tr>
<tr>
<td>14.0(√2 × 9.9)</td>
<td>0.69</td>
<td>66.87</td>
</tr>
<tr>
<td>20.8</td>
<td>0.67</td>
<td>66.87</td>
</tr>
<tr>
<td>46.6</td>
<td>0.66</td>
<td>67.62</td>
</tr>
</tbody>
</table>

From the tables 2 and 3 the following observation were made:

1. An increase in cabinet volume led to decrease of the $Q_{tc}$ of the cabinet.
2. Lowering of cabinet volume led to increase in $Q_{tc}$ of the cabinet.
3. An increase or decrease of volume raises the lower cut-off frequency of the woofer.

Where the cut off frequency means the lowest frequency the woofer can output.
4.2 GRAPHICAL REPRESENTATION OF THE TABLES 2 AND 3

4.2.1 The graph of optimum cabinet volume for a given input power to speaker drive (woofer).

This graph (Figure 3.0) shows the optimum lower cut-off frequency (lowest frequency power allowable) at 94 Hz. The woofer can produce this lowest frequency component. It is the expected minimum for most woofers. The frequency response is a linear response as expected for a good woofer.
4.2.2 The graph of a small (restricted) size cabinet (less than optimum volume) for the same input power into the same woofer.

Figure 3.1: The graph of a small size cabinet (less than optimum volume) for the same speaker input power

From this graph (figure 3.1), the output lower cut off frequency (185hz) is much higher as compared to that of the optimum volume. This means some low frequency power is lost therefore it is only possible for the woofer to produce frequencies from 185 Hz (this means a reduced frequency range). It is also clear that the gain response is not linear; therefore the desired output without distortion is not achieved using a small volume than the optimum.

Speakers that are designed to operate in very small enclosures are usually less efficient than speakers designed for larger enclosures. To make the speaker perform in a small enclosure, the suspension has to be stiff. This will raise the resonant frequency. To get a lower resonant
frequency, they must add mass to the cone of the speaker. The added mass and the stiff suspension kill the efficiency.

4.2.3 The graph of an over size (relaxed) cabinet (larger volume than the optimum volume) for the same electrical input power into the woofer.

![Graph of an over size cabinet](image)

*Figure 3.2: The graph of an over size cabinet (large volume than the optimum volume) for the same input power*

It is seen from this graph (figure 3.2) that the system has a high lower cutoff frequency as compared to the optimum volume graph (96hz), although the gain response is linear. This means that some low frequency power is lost although not as much as compared to that of small volume.

Therefore, it is concluded that the woofer has a perfect response only when the input power is matched with the right cabinet volume (optimum volume).
4.3 THE EXPERIMENTAL RESULTS

The experimental set up,

![Figure 3.3: the experimental setup](image)

Where $V_S$ is the source voltage of the signal generator, and $V_L$ is the voltage across the woofer (load). The signal generator was considered as the music signal to the speaker. Its voltage was kept constant at 1 volt peak to peak. Then the frequency was changed as the voltage across the woofer of 4 ohms internal resistance was observed and recorded. Resistor R1 was included to make readings possible, its value is almost the same as that of the woofer.

This was done first when the woofer was not in the cabinet and the repeat was done when the woofer was enclosed. The results were recorded in the tables below and graphs drawn for analysis and conclusion.
4.3.0 The experimental results of load voltage against frequency when the woofer is not in an enclosure.

Table 4: The experimental results of load voltage against frequency when the woofer is not in an enclosure.

<table>
<thead>
<tr>
<th>Frequency(Hz)</th>
<th>Source voltage (V, peak to peak) (volts)</th>
<th>Load voltage(V_L, peak to peak) (10^{-3}volts)</th>
<th>Log of frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1</td>
<td>7</td>
<td>1.7</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>15</td>
<td>2.0</td>
</tr>
<tr>
<td>500</td>
<td>1</td>
<td>16</td>
<td>2.7</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>8</td>
<td>3.0</td>
</tr>
<tr>
<td>5000</td>
<td>1</td>
<td>11</td>
<td>3.7</td>
</tr>
<tr>
<td>10000</td>
<td>1</td>
<td>16</td>
<td>4.0</td>
</tr>
<tr>
<td>15000</td>
<td>1</td>
<td>22</td>
<td>4.2</td>
</tr>
<tr>
<td>20000</td>
<td>1</td>
<td>24</td>
<td>4.3</td>
</tr>
</tbody>
</table>
4.3.1 The experimental results of load voltage against the frequency of the woofer when the woofer is placed in the cabinet.

Table 5: The experimental results of load voltage against the frequency of the woofer when the woofer is placed in the cabinet.

<table>
<thead>
<tr>
<th>Frequency(Hz)</th>
<th>Source voltage ($V_s$ peak to peak) (volts)</th>
<th>Load voltage($V_L$ peak to peak) ($10^3$ volts)</th>
<th>Log of frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1</td>
<td>28 ($10^3$ volts)</td>
<td>1.7</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>28 ($10^3$ volts)</td>
<td>2.0</td>
</tr>
<tr>
<td>500</td>
<td>1</td>
<td>28 ($10^3$ volts)</td>
<td>2.7</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>32 ($10^3$ volts)</td>
<td>3.0</td>
</tr>
<tr>
<td>1500</td>
<td>1</td>
<td>36 ($10^3$ volts)</td>
<td>3.7</td>
</tr>
<tr>
<td>10000</td>
<td>1</td>
<td>28 ($10^3$ volts)</td>
<td>4.0</td>
</tr>
<tr>
<td>15000</td>
<td>1</td>
<td>24 ($10^3$ volts)</td>
<td>4.2</td>
</tr>
<tr>
<td>20000</td>
<td>1</td>
<td>24 ($10^3$ volts)</td>
<td>4.3</td>
</tr>
</tbody>
</table>
4.3.2 Graph of woofer voltage against log frequency outside the cabinet

**Figure 3.4: graph of woofer voltage against log frequency outside the cabinet**

From the graph above, the following observation were made:

There is a peak at 100 Hz, this agrees with the manufacturer’s specification of the range of operation of the woofer, which is from 100 Hz to 10kHz. 100 Hz is the resonance frequency of the speaker.

The frequency response is not linear. Instead of the response, attenuating at higher frequency it raises, which is not an attribute of a woofer. This is because woofer outside the cabinet experiences wave interference from its back, which destructively adds with front waves to make it respond against the expectation.
4.3.3 Graph of woofer voltage against log frequency inside the cabinet

**Figure 3.5:** graph of woofer voltage against log frequency inside the cabinet

**Observation from the graph:**

From 50 Hz to 1000 Hz the frequency response of the woofer in the cabinet is linear, this is as expected for an ideal woofer at low frequency.

At 1500 Hz there is a peak, this is the second resonance of the woofer as per the manufacturer’s specification. This peak comes at a very high frequency therefore using crossover this peak can be removed as opposed to the woofer outside the cabinet where the peak is at low frequency.

At higher frequency the response drops, which is also an attribute of a good woofer and this shows that in the cabinet there is not interference from back of the woofer.
4.4 COST ANALYSIS

The tables 6 below show the cost of one single complete speaker system.

Table 6: Break down of the of the designed system cost.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost in Kshs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woofer (30 watts pioneer)</td>
<td>400</td>
</tr>
<tr>
<td>Midrange (30 watts )</td>
<td>1000</td>
</tr>
<tr>
<td>Tweeter (10 watts)</td>
<td>200</td>
</tr>
<tr>
<td>Crossover (3- way)</td>
<td>500</td>
</tr>
<tr>
<td>The (personally designed)</td>
<td>1500</td>
</tr>
<tr>
<td>Total cost of the system</td>
<td>3600</td>
</tr>
</tbody>
</table>

Table 7: The market cost of equivalent system

<table>
<thead>
<tr>
<th>System</th>
<th>Cost Kshs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pioneer (from Pioneer website)</td>
<td>12000</td>
</tr>
<tr>
<td>Sony (from Sony website)</td>
<td>8000</td>
</tr>
<tr>
<td>Cheapest in Kenyan market</td>
<td>5000</td>
</tr>
</tbody>
</table>

4.4.0 Discussion on the Table 6 and Table 7

From the tables it is clear that the total cost of designing ones own cabinet is much lower than importing a system from the bigger companies. Considering this design is as professional as the imported system, sometimes even better.

It is even cheaper as compared to systems designed in Kenyan market, whose professionalism is not guaranteed.

Therefore, it is obvious that this design presented in this project is not only professional but also feasible.
CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusions

This document has essentially covered what is required in the speaker cabinet or enclosure design and analysis. Looking at the simulated results and analysis it’s clear that if a cabinet design is done without consideration of the speaker power in relation to the cabinet volume then the required optimum result is never achieved. This is also evident from the laboratory tests done on the designed cabinet. It was clear from experiment carried out that a woofer in the cabinet performed better than that outside the cabinet.

5.2 Future work

Through this project a very important equation has been developed and successfully used to design a speaker cabinet. Despite this fact, it is quite involving to come up with the volume of the speaker especially if the data sheet of the speaker is not available.

If software is developed to use the derived equation, it will save on time and even look professional other than doing the real mathematical calculations. Through the software, it will be easy to include a database that will contain all the required parameters (that is manually updated or online updated).
REFERENCE

1. John Berwick; *Loudspeaker and Headphone Handbook*; © 2001; Reed Educational and Professional Publishing Ltd.


APPENDIX

The sketch of the cabinet designed.

The explanation of some terms used

1. Loudspeaker- means the speaker system
2. Speaker drive- means woofer, midrange or tweeter. Whenever as specific speaker drive is explained, it has been indicated.
3. The cabinet, box and enclosure mean the same thing.