Introduction to loudspeaker modelling & design

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Contents

1 Introduction

This article serves as an introduction to the fundamental operation of loudspeakers, how the can be modelled, how they can be designed using LTSPICE simulation in the design process. Basic loudspeaker parameters known as Thiele-Small parameters will be described and loudspeaker models for closed box- and vent box-loudspeaker systems introduced. Moreover vented box alignment theory will be presented and a design tool provided for vented box designs. Finally two design examples including simulations of the frequency response in LTSPICE will be presented.

2 Loudspeaker modelling

2.1 Basic loudspeaker operation

Loudspeakers and loudspeaker models are well described in literature [2] but the basic concepts are presented in this sections.
A loudspeaker works by converting an electrical signal into motion of its' diaphragm, creating pressure differences in air which we perceive as audio. Fig. 1 shows the conceptual elements of a loudspeaker unit.

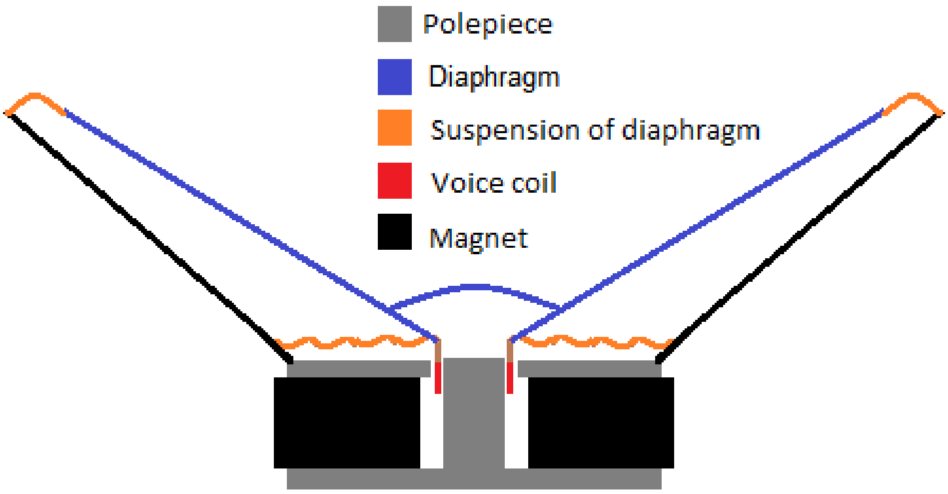

Figure 1: Conceptual loudspeaker driver

The signal enters the voice coil, this generates a magnetic field causing a displacement of the voice coil due to the static magnetic field of the permanent magnet. This displacement is transferred to the diaphragm and emitted as sound. We can split the loudspeaker into three different domains:

- Electrical domain
- Mechanical domain
- Acoustical domain

The electrical domain is characterised by the voice coil with a given DC resistance and self-inductance, R_e and L_e. As mentioned the electrical signal is converted to a mechanical motion. The strength of this coupling from electrical to mechanical domain is related to the force factor Bl, which is the product of the magnetic field strength of the static magnet in the voice coil gap, B, and the length of the voice coil (eg. the wire) in the static magnetic field, l.

The mechanical domain is characterised by the mass, M_{MD}, of the diaphragm, the compliance, C_{MS}, of the suspension and a mechanical damping, R_{MS}. The mass, the compliance and the damper will introduce a resonance frequency, f_S, with a given Quality factor, Q_{MS}, the mechanical Q-factor. At the resonance frequency the driver will reach its' maximum impedance. The electrical domain is also characterised by a Q-factor, Q_{ES} which is dependent on Bl, R_e, M_{MD} and C_{MS}. Combining the mechanical and electrical Q-factors results in a total Q-factor known as Q_{TS}. The mechanical motion is converted to acoustical sound through the diaphragm and the strength of this coupling is related to the area of the driver diaphragm, S_D.

The acoustical domain is characterised by the acoustical impedance in front, Z_{AF}, and behind , Z_{AB}, the diaphragm. Normally a loudspeaker will be mounted in some kind of enclosure and therefore a parameter known as the volume compliance, V_{AS}, is introduced. The volume compliance corresponds to the equivalent volume of air which, when compressed by a piston having the same area as the driver diaphragm, will have the same compliance (mechanical spring) as the mechanical compliance of the driver suspension C_{MS}.

All these parameters are known as Thiele-Small parameters and a well described in literature, [3] and [4] and are listed in table 1. These parameters are normally given in datasheets for drivers and are used when designing enclosures for the the loudspeaker driver, eg. cabinets.

Symbol	**Parameter**
R_e	DC resistance of voice coil
L_e	Self inductance of voice coil
Bl	Force factor
M_{MD}	Mass of diaphragm
C_{MS}	Compliance of suspension
R_{MS}	Mechanical damping
f_S	Resonance frequency
Q_{MS}	Mechanical quality factor
Q_{ES}	Electrical quality factor
Q_{TS}	Total quality factor
S_D	Area of diaphragm
V_{AS}	Equivalent volume

Table 1: Thiele-Small parameters

A typical measurement of the impedance of a loudspeaker woofer is shown in fig. 2. From the measurement one can indentify the resonance frequency, the DC resistance and the self inductance which causes the impedance to increase at high frequencies.

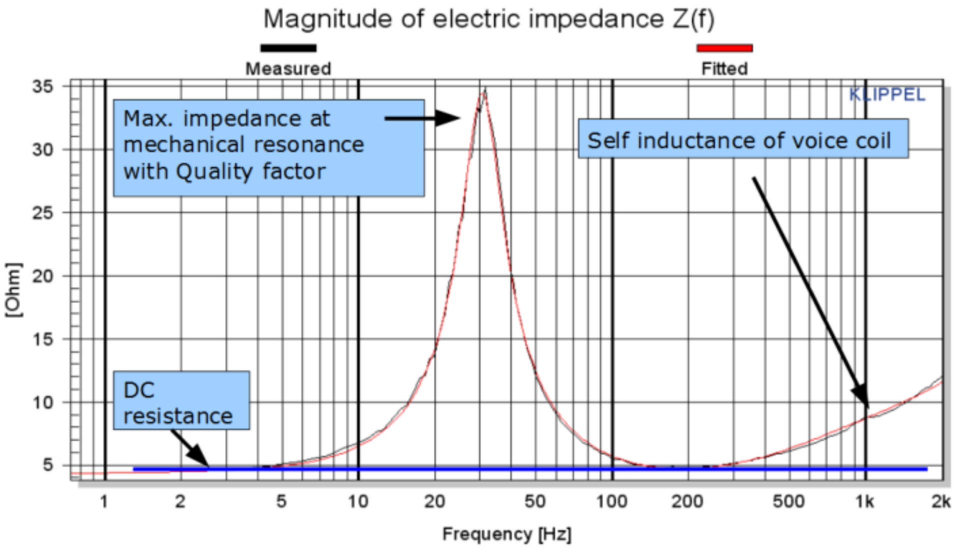

Figure 2: Impedance measurement of typical loudspeaker woofer

2.2 Infinite baffle loudspeaker

The infinite baffle loudspeaker is a loudspeaker standard where the driver is mounted in an infinite large wall (infinite baffle). This corresponds to the loudspeaker being mounted in an infinite large box. An equivalent electrical circuit can be implemented as shown in fig. 3.

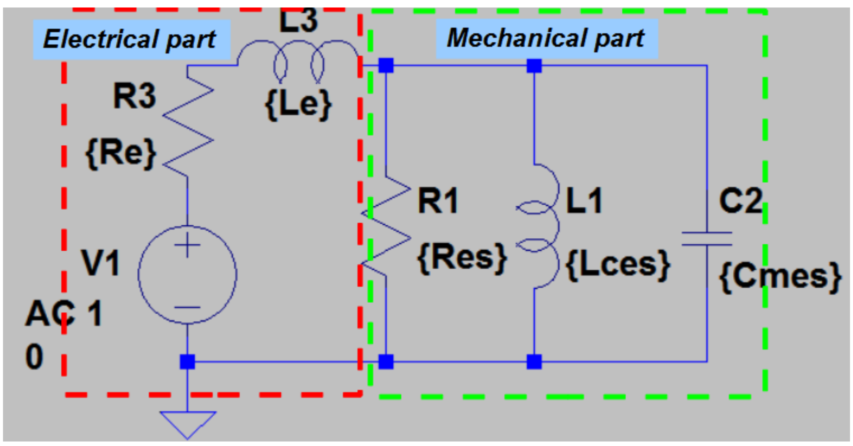

Figure 3: Equivalent circuit for driver mounted in infinite baffle

The inductance, L_{ces}, corresponds to the compliance of the suspension, the capacitance, C_{mes} corresponds to the mass of the diaphragm and the resistance, R_{es}, corresponds to the mechanical damping. Together these three components emulate the mechanical characteristics of the driver while L_e and R_e are the electrical self inductance and the DC resistance of the voice coil. Since the driver is mounted in free air the acoustical load will be the same on each side of the diaphragm and therefore it can be neglected. Knowing the Thiele-Small parameters values for the components can be found by solving for L_{ces}, C_{mes} and R_{es} in:

$$Q_{ES} = 2\pi f_S C_{mes} R_E \tag{1}$$

$$Q_{MS} = 2\pi f_S C_{mes} R_{es} \tag{2}$$

$$f_S = \frac{1}{2\pi\sqrt{C_{mes} L_{ces}}} \tag{3}$$

2.3 Closed box loudspeaker

A closed box loudspeaker is a very simple loudspeaker configuration where the driver is mounted in a sealed enclosure. This type of loudspeaker is one the most common loudspeakers in the industry.
When the loudspeaker driver is mounted in an enclosure the acoustical load on each side of the diaphragm is unequal and therefore the acoustical part must be taken into account. The volume of the enclosure, V_{AB}, works as an acoustical compliance (spring) and can be modelled with the inductor, L_{ceb}, in the electrical equivalent circuit shown in fig. 4.

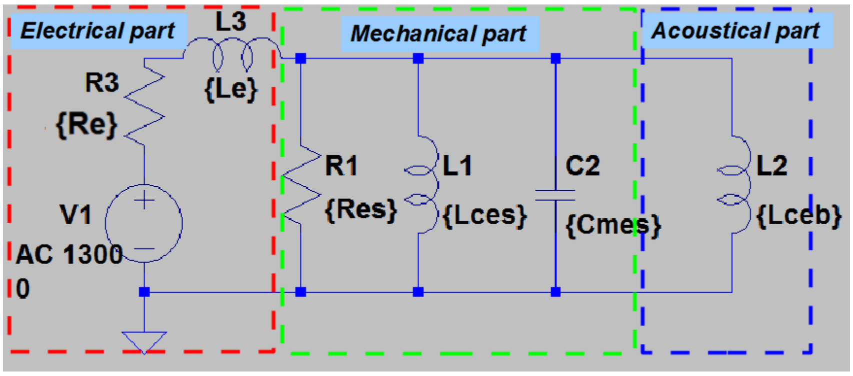

Figure 4: Equivalent circuit for closed box loudspeaker

This introduces a new parameters known as the compliance ratio, α. α is simply the ratio between the equivalent volume and the volume of the enclosure which the driver is mounted in. This corresponds to the ratio between the inductances.

$$\alpha = \frac{V_{AS}}{V_{AB}} = \frac{L_{ces}}{L_{ceb}} \tag{4}$$

This additional volume compliance will add up together the equivalent volume compliance and shift the resonance frequency and quality factor of the system. If it is assumed that the enclosure is lossless the resonance frequency and the quality factor of the closed box system becomes:

$$f_C \approx \sqrt{1+\alpha} f_S \tag{5}$$

$$Q_{TC} \approx \sqrt{1+\alpha} Q_{TS} \tag{6}$$

It is seen that the system cannot achieve a quality factor which is lower than the total quality factor of the driver. The -3dB cut-off frequency, f_l, eg. the half power frequency, can be calculated from:

$$f_l = f_C \left(\left(\frac{1}{2Q_{TC}^2} - 1 \right) + \sqrt{\left(\frac{1}{2Q_{TC}^2} - 1 \right)^2 + 1} \right)^{1/2} \tag{7}$$

$$\tag{8}$$

2.4 Vented box loudspeaker

The vented box loudspeaker is also a very common speaker which uses an additional resonance frequency, generated by a vent in the box, to increase the low frequency output. There a many different kinds of vented box optimal alignments and the some the most common are described in this section.
The vent in the box introduces an additional resonance frequency, f_B. The mass of the air in the vent will resonate with the volume of the enclosure. This type of resonator is known as a Helmholtz resonator. The mass of the vent can be modelled as an capacitance, C_{mep} in an electrical equivalent circuit. The vented box enclosure quality factor, Q_L, is related to the enclosure leakage resistance which can be modelled as a resistance, R_{el}, in the electrical equivalent circuit. Q_L will typically be small for big enclosures ($Q_L = 5 - 10$), meaning high enclosure leakage and large for small enclosures ($Q_L = 10 - 20$), meaning low enclosure leakage. Fig. 5 shows the electrical equivalent circuit for the vented box loudspeaker.

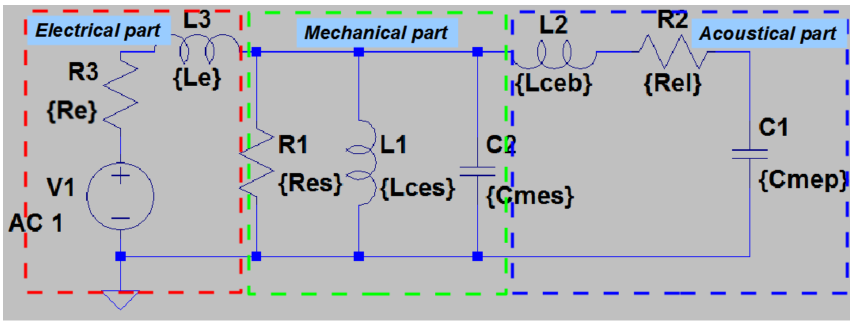

Figure 5: Equivalent circuit for vented box loudspeaker

Knowing the Helmholtz resonance frequency, f_B, and enclosure volume, V_{AB}, one can assume a given Q_L value and the find the needed component values for electrical equivalent circuit by solving for R_{el} and C_{mep} in:

$$f_B = \frac{1}{2\pi\sqrt{C_{mep} L_{ceb}}} \tag{9}$$

$$Q_L = \frac{1}{2\pi f_B C_{mep} R_{el}} \tag{10}$$

For a given driver there will be an optimal alignment. These a described in the following subsections. Note that the procedure of calculating an alignment will result in a Q_{TS} that the driver must have to be suited and not the other way around.

2.4.1 General steps for alignments

Alignments[1] of vented box loudspeakers systems is based on the magnitude squared function $|G_V(j2\pi f)|^2$ as explained by [2]. It's given by:

$$|G_V(j2\pi f)|^2 = \frac{(f/f_0)^8}{(f/f_0)^8 + A_3(f/f_0)^6 + A_2(f/f_0)^4 + A_1(f/f_0)^2 + 1} \tag{11}$$

where A_1, A_2 and A_3 are coefficients dependent on three other coefficients:

$$A_1 = a_1^2 - 2a_2 \tag{12}$$

$$A_2 = 2 + a_2^2 \tag{13}$$

$$A_3 = a_3^2 - 2a_2 \tag{14}$$

The formula for determine the a coefficients are dependent on the choice of alignment. Once the coefficients are calculated, the alignments parameters can be calculated using the guide from [2] page 140.

1. Find positive real roots of d in:

$$d^4 - A_3 d^3 - A_2 d^2 - A_1 d - 1 = 0 \tag{15}$$

2. Find positive real roots of r in:

$$r^4 - (a_3 Q_L) r^3 - (a_1 Q_L) r - 1 = 0 \tag{16}$$

3. Use the values for r and d to determined the alignment parameters:

$$h = \frac{f_B}{f_S} = r^2 \tag{17}$$

$$q = \frac{f_l}{f_S} = r\sqrt{d} \tag{18}$$

$$Q_{TS} = \frac{r^2 Q_L}{a_1 r Q_L - q} \tag{19}$$

$$\alpha = \frac{V_{AS}}{V_{AB}} = r^2 \left(a_2 - \frac{1}{Q_L Q_{TS}} - r^2 \right) - 1 \tag{20}$$

Having a specific driver with resonance frequency f_S, the Helmholtz resonance f_B, the -3dB cut-off frequency f_l and the cabinet volume V_{AB} can be calculated using eq. 17, 18 and 20.

[1] Note that section 2.4.1, 2.4.2, 2.4.3 and 2.4.4 is borrowed from [5] by the same author

Q_L	5	8	11	14	17	20
Q_{TS}	0.4144	0.4019	0.3965	0.3934	0.3915	0.3901

Table 2: B4 Q_{TS} values for different values of Q_L

2.4.2 4th order Butterworth (B4)

The B4 alignment is the 4th the special case where $A_1 = A_2 = A_3 = 0$. Applying this to eq. 11, 15 and 16 we obtain the magnitude squared function for the B4 alignment and the d and r values.

$$|G_V(j2\pi f)|^2 = \frac{(f/f_0)^8}{(f/f_0)^8 + 1} \tag{21}$$

$$d = 1 \tag{22}$$

$$r = 1 \tag{23}$$

Knowing that all A values is zero we obtain the a values from eq. 14:

$$a_1 = \sqrt{2a_2} \tag{24}$$

$$a_2 = 2 + \sqrt{2} \tag{25}$$

$$a_3 = \sqrt{2a_2} \tag{26}$$

Note that there for a given Q_L value only can be calculated one Q_{TS} value for the B4 alignment. In practice this means that a pure B4 alignment rarely is implemented for a given driver. The Q_{TS} values have been calculated for Q_L values ranging $5 - 20$. Some of them are listed in table 2.

A butterworth alignment will result in a -3dB cutoff frequency equal to the resonance frequency of the driver.

2.4.3 3rd order quasi Butterworth (QB3)

The QB3 alignment is used for drivers having a lower Q_{TS} value than needed for a B4 alignment. The magnitude squared function is obtained using [2] and is given by:

$$|G_V(j2\pi f)|^2 = \frac{(f/f_0)^8}{1 + B^2(f/f_0)^2 + (f/f_0)^8} \tag{27}$$

where B is an alignment parameter. For $B = 0$ the magnitude square function reduces to eq. 21 and the alignment becomes at pure B4 alignment. Moreover we can see that $B^2 = A_1$ while $A_2 = A_3 = 0$. Using eq. 14 one can derive the a values:

$$B^2 = a_1^2 - 2a_2 \tag{28}$$

$$a_1 = \frac{a_2^2 + 2}{2a_3} \tag{29}$$

$$a_2 > 2 + \sqrt{2} \tag{30}$$

$$a_3 = \sqrt{2a_2} \tag{31}$$

To design a QB3 alignment one must determine B and used the equations for the a values to solve for a_2, then calculate a_1 and a_3 and then finally use the procedure described in section 2.4.1. All QB3 alignments will result in a -3dB cut-off frequency that is higher than the resonance frequency of the driver and a cabinet volume that is smaller than the equivalent volume, of the driver.

2.4.4 Chebyshew equal-ripple (C4)

As the name indicates the C4 alignment allows the frequency response to have a ripple. This alignment is used for Q_{TS} values above the ones required for a B4 alignment. The magnitude squared function is given by:

$$|G_V(j2\pi f)|^2 = \frac{1+\epsilon^2}{1+\epsilon^2 C_2^4(f_n/f)} \tag{32}$$

ϵ is an alignment parameter related to another parameter k used for the calculation of the alignment and $C_2^4(f_n/f)$ is the fourth order chebyshew polynomial. Moreover ϵ determines the ripple allowed in the alignment.

$$k = \tanh\left[\frac{1}{4}\sinh^{-1}\left(\frac{1}{\epsilon}\right)\right] \tag{33}$$

$$C_2^4(fn/f) = 8(f_n/f)^4 - 8(f_n/f)^2 + 1 \tag{34}$$

$$dB_{ripple} = 10log\left(1+\epsilon^2\right) \tag{35}$$

The frequency f_n is a normalization frequency used in the chebyshew polynomial. This frequency is related to the -3dB cutoff frequency f_l (see [2] p. 142). k is used to calculate another parameter D:

$$D = \frac{k^4 + 6k^2 + 1}{8} \tag{36}$$

Having D and k, the a values can be determined using the following equations from [2] p. 143:

$$a_1 = \frac{k\sqrt{4+2\sqrt{2}}}{D^{1/4}} \tag{37}$$

$$a_2 = \frac{1+k^2\left(1+\sqrt{2}\right)}{D^{1/2}} \tag{38}$$

$$a_3 = \frac{a_1}{D^{1/2}}\left(1-\frac{1-k^2}{2\sqrt{2}}\right) \tag{39}$$

To design a C4 alignment one should specify ϵ then calculate k, D and the a coefficients and then proceed with the general procedure described in section 2.4.1. A C4 alignment will result in a -3dB cutoff frequency that is lower than the resonance frequency of the driver. For many C4 alignment the cabinet volume will be bigger than the equivalent volume of the driver.

2.4.5 Designing with a given driver

As mentioned earlier in this section the general alignment procedure will generated Q_{TS} value which the driver must comply with if the design should work. In order to make a design with a given driver one should calculate all possible alignments and find the one best suited. This have been done for enclosure quality factor of $Q_L = 5$, $Q_L = 10$ and $Q_L = 15$ and fig. 6, 7 and 8 shows Q_{TS} and the alignment parameters, h and q, as a function of α. The blue graph corresponds to Q_{TS}, the green curve corresponds to h and the red curve corresponds to q. The figures can be used as a design tool when designing with a given driver. One should just use the following steps.

1. Find the Q_{TS} value of the driver on the left side of the chart and draw a horizontal line that intersects with the Q_{TS} curve.
2. From the intersection draw a vertical line that intersects with the h and q curve and the x-axis where α can be evaluated.
3. Draw two horizontal lines from the intersections between the vertical line and the h and q curves.
4. Read the value of the alignments parameters h and q from the right y-axis.
5. Now the cabinet volume, V_{AB}, the Helmholtz resonance, f_B, and the -3dB cut-off frequency can be evaluated from eq. 17, 18 and 20.

Once a suited alignment is found and the Helmholtz resonance, f_B, and box volume, V_{AB}, has been calculated the vent itself can be designed by using:

$$L_p = \left(\frac{c}{2\pi f_B}\right)^2 \frac{S_P}{V_{AB}} - 1.463\sqrt{\frac{S_P}{\pi}} \tag{40}$$

Where L_p is the length of the vent, S_P is the cross section area of the vent and $c \approx 345$m/s is the speed of sound.

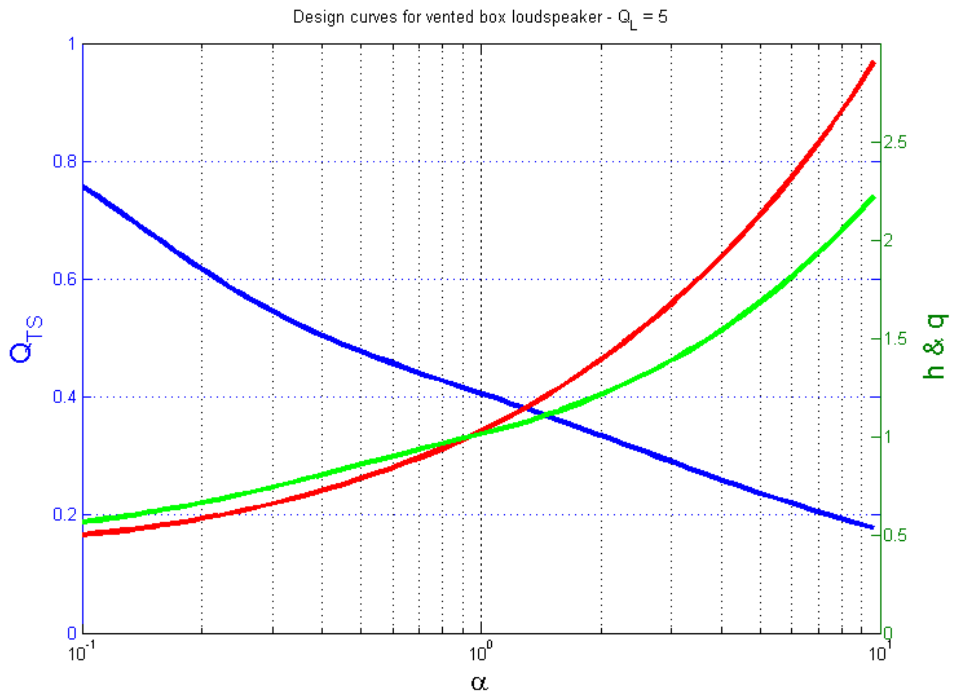

Figure 6: Design tool for vented box - $Q_L = 5$

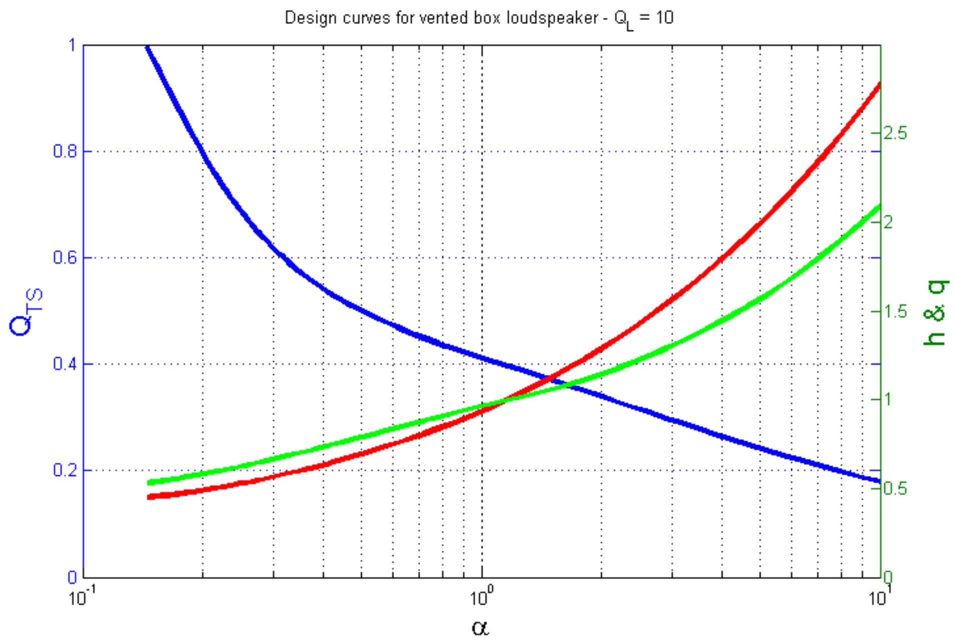

Figure 7: Design tool for vented box - $Q_L = 10$

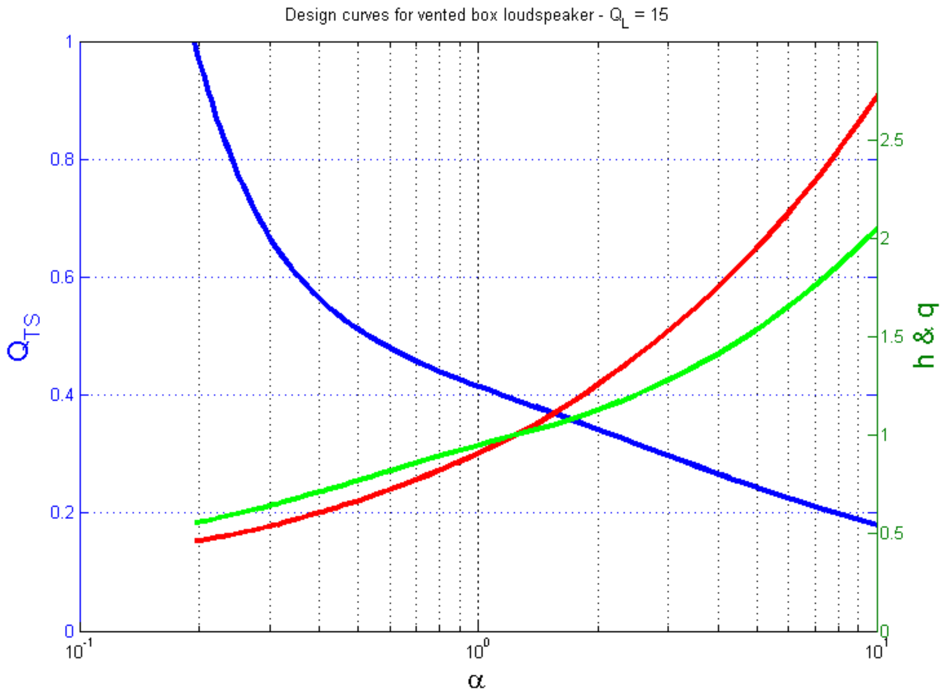

Figure 8: Design tool for vented box - $Q_L = 15$

3 Design example and simulations

This section presents design examples of a closed box- and vented box-loudspeaker including simulations using the LTSPICE software. The relevant Thiele-Small parameters for the loudspeaker driver used in this section are listed in table 3

Symbol	**Value**
R_e	6.1 Ω
L_e	0.11 mH
f_S	105 Hz
Q_{MS}	1.8
Q_{ES}	1.23
Q_{TS}	0.72
S_D	36.3 cm^2
V_{AS}	1 L

Table 3: Thiele-Small parameters

3.1 Design and simulation of closed box loudspeaker

The enclosure volume is chosen to be $V_{AB} = 0.5$ liters as an initial starting point. The compression ratio, the closed box resonance frequency, the closed box quality factor and the -3dB cut-off frequency is then calculated using eq. 4, 5, 6 and 8.

$$\alpha = \frac{1\text{L}}{0.5\text{L}} = 2 \tag{41}$$

$$Q_{TC} \approx \sqrt{1+2} \cdot 105\text{Hz} = 182\text{Hz} \tag{42}$$

$$Q_{TC} \approx \sqrt{1+2} \cdot 0.72 = 1.24 \tag{43}$$

$$f_l = 182\text{Hz} \cdot \left(\left(\frac{1}{2 \cdot 1.24^2} - 1 \right) + \sqrt{\left(\frac{1}{2 \cdot 1.24^2} - 1 \right)^2 + 1} \right)^{1/2} \downarrow \tag{44}$$

$$f_l = 133\text{Hz} \tag{45}$$

It is seen that the -3Db cut-off frequency is rather high and not satisfactory. BHy increasing the volume the low frequency response can be increase. By choosing the enclosure volume to be $V_{AB} = 1.5$ liters we get:

$$\alpha = \frac{1\text{L}}{1.5\text{L}} = 0.67 \tag{46}$$

$$Q_{TC} \approx \sqrt{1+0.67} \cdot 105\text{Hz} = 136\text{Hz} \tag{47}$$

$$Q_{TC} \approx \sqrt{1+0.67} \cdot 0.72 = 0.93 \tag{48}$$

$$f_l = 136\text{Hz} \cdot \left(\left(\frac{1}{2 \cdot 0.93^2} - 1\right) + \sqrt{\left(\frac{1}{2 \cdot 0.93^2} - 1\right)^2 + 1}\right)^{1/2} \downarrow \tag{49}$$

$$f_l = 111\text{Hz} \tag{50}$$

Evidently a better low frequency response is achieved and therefore this design is used to construct a simulation model LTSPICE. The loudspeaker model from fig. 4 is used to built the simulation model in LTSPICE. The values of L_e and R_e can be directly inserted in the simulation model. The values of R_{es}, C_{mes}, L_{ces} and L_{ceb} can be determined using eq. 1, 2, 3 and 4.

$$C_{mes} = \frac{1.24}{2\pi \cdot 105\text{Hz} \cdot 6.1\Omega} = 306\mu\text{F} \tag{51}$$

$$R_{es} = \frac{1.8}{2\pi \cdot 105\text{Hz} \cdot 306\mu\text{F}} = 8.9\Omega \tag{52}$$

$$L_{ces} = \frac{1}{(2\pi \cdot 105\text{Hz})^2 \cdot 306\mu\text{F}} = 7.5\text{mH} \tag{53}$$

$$L_{ceb} = \frac{7.5\text{mH}}{0.67} = 11.2\text{mH} \tag{54}$$

Now the simulation model can be constructed with proper component values in LTSPICE and fig. 9 shows it.

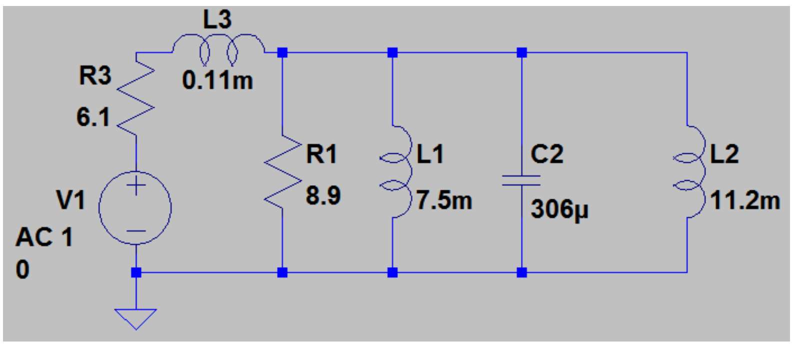

Figure 9: LTSPICE simulation model for designed closed box loudspeaker

Setting up an AC analysis in LTSPICE and measuring the current in C_{mes} gives the frequency response curve shown in fig. 10. From the LTSPICE simulation we can see that the response curve looks fine and with -3dB cut-off frequency close to the predicted.

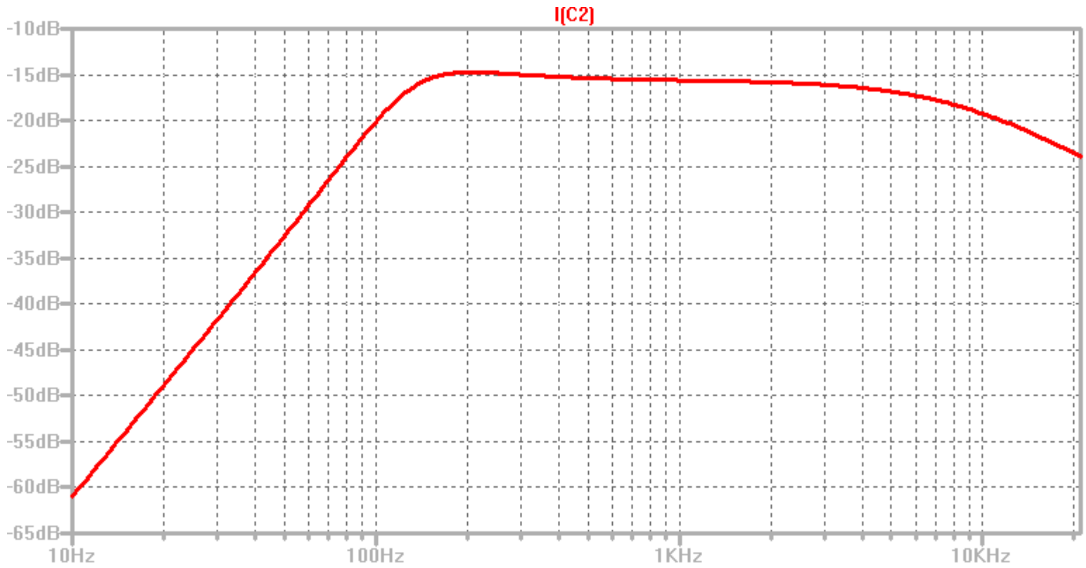

Figure 10: LTSPICE simulation frequency response for designed closed box loudspeaker

3.2 Design and simulation of vented box loudspeaker

It is desired to make an optimal vented box alignment. Since the enclosure volume is expected to be fairly small, therefore an enclosure quality factor of $Q_L = 15$ is chosen. We can use fig. 8 to find the optimum alignment parameters using the steps presented in section 2.4.5. Fig. 11 shows how the alignment parameters are obtained from the graph.

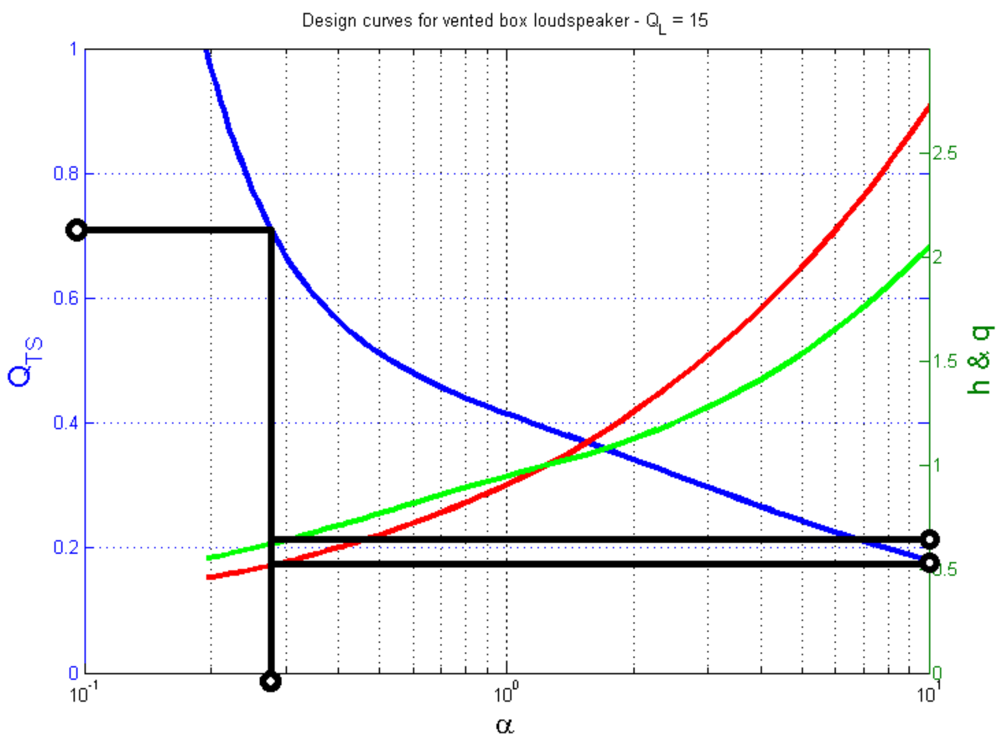

Figure 11: Use of design tool - $Q_L = 15$

The obtained alignment parameters are listed in table 4.
From this we can calculate the needed enclosure volume, the Helmholtz resonance and the -3dB cut-off frequency using eq. 17, 18 and 20

Symbol	Value
α	0.28
h	0.6
q	0.51

Table 4: Obtained alignment parameters

$$f_B = 0.6 \cdot 105\text{Hz} = 63\text{Hz} \tag{55}$$

$$f_l = 0.51 \cdot 105\text{Hz} = 53\text{Hz} \tag{56}$$

$$V_{AB} = \frac{1\text{L}}{0.28} = 3.6\text{L} \tag{57}$$

Now we can start building the a simulation model in LTSPICE similar to the one shown in fig. 5. The values of L_e and R_e can be directly inserted in the simulation model. The values of R_{es}, C_{mes}, L_{ces} and L_{ceb} can be determined using eq. 1, 2, 3 and 4.

$$C_{mes} = \frac{1.24}{2\pi \cdot 105\text{Hz} \cdot 6.1\Omega} = 306\mu\text{F} \tag{58}$$

$$R_{es} = \frac{1.8}{2\pi \cdot 105\text{Hz} \cdot 306\mu\text{F}} = 8.9\Omega \tag{59}$$

$$L_{ces} = \frac{1}{(2\pi \cdot 105\text{Hz})^2 \cdot 306\mu\text{F}} = 7.5\text{mH} \tag{60}$$

$$L_{ceb} = \frac{7.5\text{mH}}{0.28} = 26.8\text{mH} \tag{61}$$

Moreover the component values for C_{mep} and R_{el} can be determined using eq. 9 and 10.

$$C_{mep} = \frac{1}{(2\pi \cdot 63\text{Hz})^2 \cdot 26.8\text{mH}} = 238\mu\text{F} \tag{62}$$

$$R_{el} = \frac{1}{2\pi \cdot 63\text{Hz} \cdot 238\mu\text{F} \cdot 15} = 0.71\Omega \tag{63}$$

Now the simulation model can be constructed with proper component values in LTSPICE and fig. 12 shows it.
In order to measure the frequency response a small capacitor of 2μF is placed in parallel with L_{ceb} as shown in fig. 13.
When performing an AC analysis the current in this capacitor will be the frequency response. The response curve is shown in fig. 14. From the frequency response we can see that a little ripple indicating that the alignment is a C4 equal ripple alignment. The -3dB cut-off frequency from the frequency response correlates quite well with the one calculated earlier in this section.
For the vent design a rectangular shape is chosen. The shape could also be circular. The vent dimensions is chosen to be $1.5X1.5\text{cm}^2$ thus obtaining a port cross section area of:

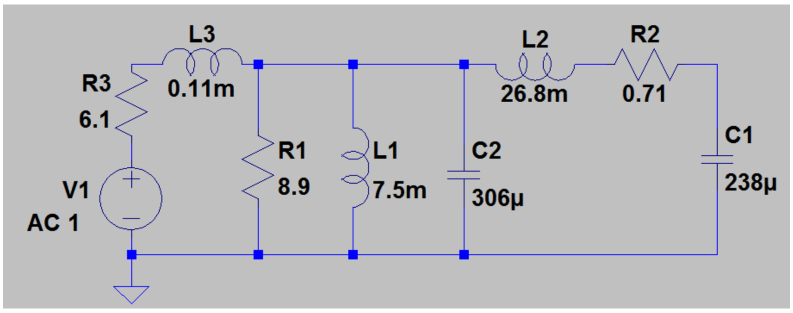

Figure 12: LTSPICE simulation model for designed vented box loudspeaker

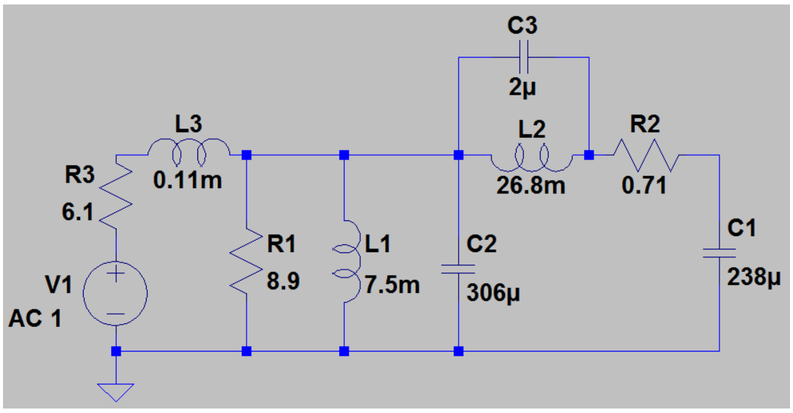

Figure 13: LTSPICE simulation model for designed vented box loudspeaker - measurement configuration

$$S_P = 0.015\text{m} \cdot 0.015\text{m} = 0.225 \cdot 10^{-3}\text{m}^2 \tag{64}$$

The length of the port can then be determind using eq. 40.

$$L_p = \left(\frac{345\text{m/s}}{2\pi \cdot 63\text{Hz}}\right)^2 \frac{0.225 \cdot 10^{-3}\text{m}^2}{3.6 \cdot 10^{-3}\text{m}^3} - 1.463\sqrt{\frac{0.225 \cdot 10^{-3}\text{m}^2}{\pi}} = 3.6\text{cm} \tag{65}$$

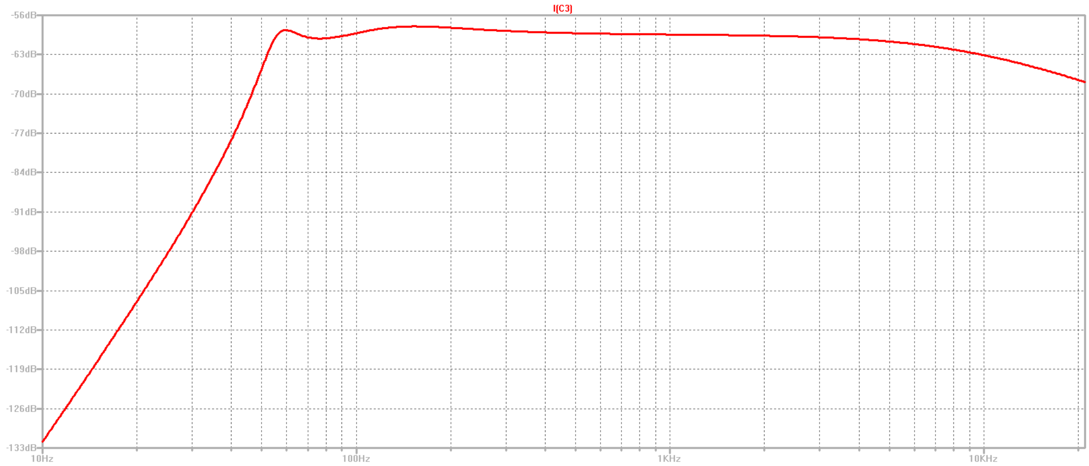

Figure 14: LTSPICE frequency response for designed vented box loudspeaker

4 Conlusion

Throughout this article various loudspeaker models and loudspeaker designs has been presented. Theory concerning vented box alignments has been described and from this a design tool has been developed and provided. It can be concluded that electrical equivalent models can be used to emulate the electrical, mechanical and acoustical part of a loudspeaker. Moreover these models can be used in SPICE simulations to predict the frequency response of a loudspeaker design.

References

[1] Richard H. Small, "Vented-Box Loudspeaker Systems Part I: Small-Signal Analysis", School of electrical engineering, The University of Sydney, 2006.

[2] W. Marshall Leach, Jr. "Introduction to Electroacoustics and Audio Amplifier Design", Kendall/Hunt Publishing Company, 2003.

[3] A. N. Thiele, "Loudspeakers in vented boxes, Parts I and II", J. Audio Eng. Soc., vol. 19 pp. 382-392 (May 1971); pp. 471-483 (June 1971),

[4] R. H. Small, "Closed-box loudspeaker systems", J. Audio Eng. Soc., vol 20 pp. 383-395 (June 1972).

[5] N. E. Iversen, "Tuning of vented box loudspeaker systems", Technical University of Denmark (May 2013).