Design of loudspeaker enclosures: closed box

Castells Ramón, Francisco (fcastells@eln.upv.es)

Departamento de Ingeniería Electrónica
Universitat Politècnica de València

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Contents

1 Summary of key ideas

This document provides the insights about the design process of closed boxes (also known as sealed enclosures). This includes the correct choice of the driver, how the box modifies the response of the loudspeaker system as a whole and the evaluation of the system performance. Figure 1 illustrates this approach, including the key aspects involved in each parts.

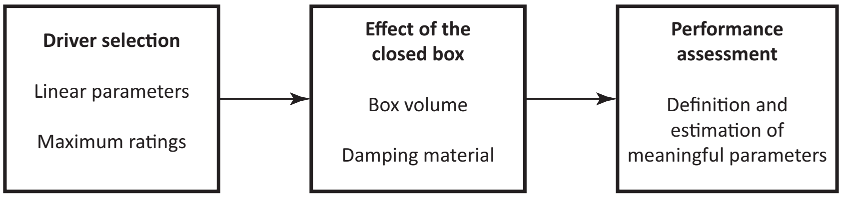

Figure 1: Overview of the steps involved in the design of sealed enclosures.

2 Introduction

Imagine that a speaker (only the transducer) is radiating in free space. Would this configuration be correct? What do you think about it? Probably your answer is no, as you have generally seen it mounted on a box or on a large baffle. But, which is the reason for that?

Actually, there is a big problem with speakers radiating in free space. The main drawback is that the radiation from the rear side is in antiphase with respect to front side radiation. At low frequencies, where the wavelength is larger than the driver's diameter, the radiation from front and rear sides cancel each other (if not completely, sound is dramatically attenuated). This phenomenon is known as acoustic short circuit, and is illustrated in Figure 2. As a consequence of it, low frequencies cannot be propagated properly.

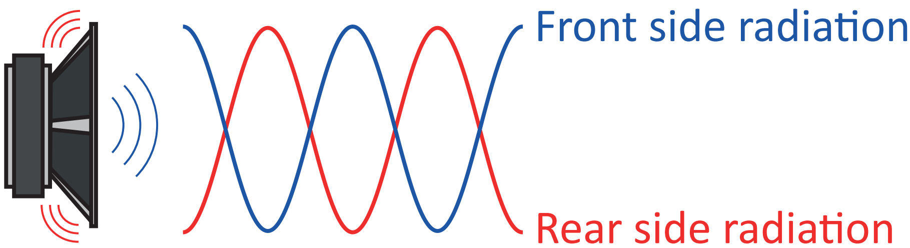

Figure 2: Illustration of the acoustic short circuit: front and rear waves are in antiphase.

Mounting the speaker on a closed box is a relatively simple solution to overcome this problem, as it blocks the rear wave. Closed boxes are characterized by an internal volume and are usually filled in with damping material (see Figure 3). The air within the enclosure adds an extra stiffness to the mechanical stiffness of the driver. Therefore, all parameters that rely on the driver's compliance will be modified by the effect of the box. The joint interaction of the driver and the box will determine the performance of the system as a whole, as will be detailed in section 4.

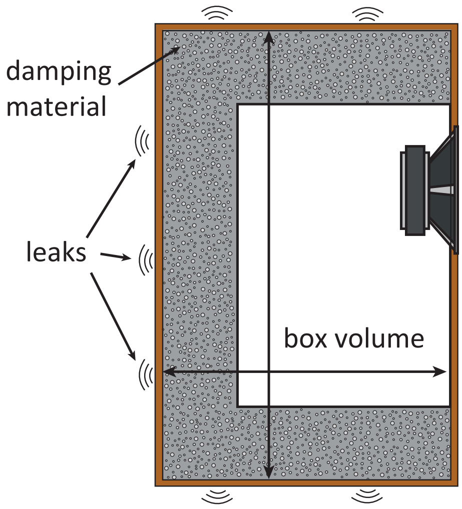

Figure 3: Scheme of a closed box.

2.1 Previous requirements

To achieve the full learning potential of this material you should master the concepts regarding the dynamic speaker, including the equivalent circuit, electromechanical and linear parameters as well as the characteristic curves.

3 Objectives

After reading this document you will be able to:

- Identify the key parameters of the driver and select an appropriate speaker.
- Determine at which extent the volume of the box and the damping material will modify the linear parameters of the driver and obtain the new parameters of the loudspeaker system.
- Evaluate and specify the performance of the loudspeaker.

4 Development

4.1 Overview of the parameters involved

In closed-box designs there are two parts involved: the woofer and the enclosure. The combination of both and the interaction of their respective parameters will define the performance of the loudspeaker system. The main parameters involved are summarized in Table 1 and Table 2.

Table 1: Parameters of the driver and the enclosure.

Woofer parameters	Enclosure parameters
f_{s}: resonance frequency	V_{B}: physical box volume
Q_{ES} and Q_{TS}: quality factors	γ: increase of the acoustical volume
V_{AS}: equivalent air volume to C_{MS}	V_{AB}: apparent or acoustical volume
η_0: efficiency	α: volume ratio $V_{\mathrm{AS}}/V_{\mathrm{AB}}$
X_{max}: maximum linear displacement	Q_{A}: quality factor due to damping material
peak P_{E}: maximum input power	Q_{L}: quality factor due to leakage

Table 2: Parameters that define the response and performance of the loudspeaker system.

Loudspeaker response	Loudspeaker performance
	V_{B}: physical box volume
f_{c}: system's resonance frequency	f_6: lower cutoff frequency
Q_{TC}: system's quality factor	LF Peak (or LF boost)
	$\mathrm{SPL}_{\mathrm{max}}$: maximum achievable SPL

4.2 Effects of the box

Sealed enclosures are characterized by a fixed volume that behaves as an acoustical compliance C_{AB}. Moreover, the losses due to the absorbent material and leakage can be modeled by the acoustical resistances R_{AB} and R_{L}, respectively. Actually, the most comprehensive way to understand the response of closed boxes is through the analysis of its equivalent circuit. How do you think the equivalent circuit of the overall system will be? To answer this question, have a look to Figure 4. As you will appreciate, these acoustical elements are appended at the right side. The mechanical circuit of the driver and the acoustical parameters of the box are coupled through the transformation ratio S_{D}.

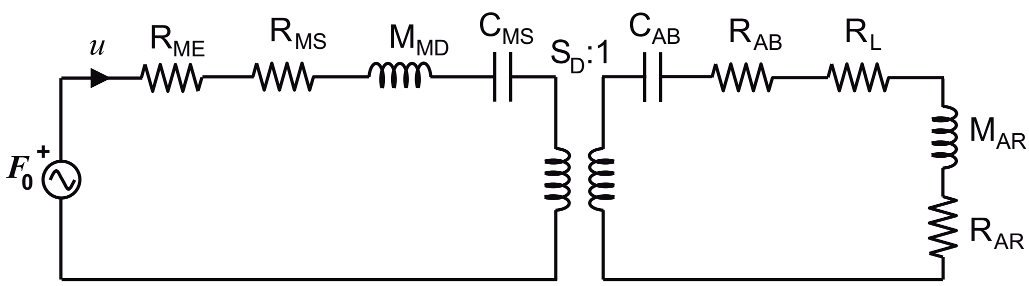

Figure 4: Equivalent circuit of a closed box.

The important question now is to determine the changes in the response of the system. Due to stiffness increase, the overall compliance is decreased by (1+α), where

$$\alpha = \frac{V_{\mathrm{AS}}}{V_{\mathrm{AB}}} \tag{1}$$

and $V_{\mathrm{AS}} = \gamma V_{\mathrm{B}}$, being V_{AB} the apparent volume and V_{B} the physical volume of the box. The factor γ is associated with the increase of the apparent volume due to filling with absorbent material, with values theoretically ranging between 1 and 1.4 (the heavier the filling the larger the value of γ). For practical purposes, it is typically considered $\gamma = 1.2$ in boxes with filling and $\gamma = 1$ in boxes with no filling.

At this point, do you think that filling with damping material would be convenient in closed-box designs? The answer is affirmative, as enclosures with filling require a lower physical volume to obtain the same apparent volume. To understand the importance this, think that size matters in loudspeaker design, so V_{B} is not only a parameter related to the enclosure, but also is one of the parameters that define the performance of the loudspeaker system (see that V_{B} not only appears in Table 1 but also in Table 2). Therefore, heavy filling is generally reccomended, as it allows reducing the volume of the cabinet.

4.3 Loudspeaker response

By the effect of the box, any linear parameter where the compliance and/or the mechanical resistances are involved will be modified. How do you think the resonance frequency, quality factor and efficiency will be affected? Are you able to answer to this? The solution is as follows:

- **Resonance frequency:** Remind that

$$f_{\mathrm{s}} = \frac{1}{2\pi\sqrt{M_{\mathrm{MS}}C_{\mathrm{MS}}}} \tag{2}$$

  As a consequence, the resonance frequency of the loudspeaker system f_{c} increases with respect to f_{s}:

$$f_{\mathrm{c}} = f_{\mathrm{s}}\sqrt{1+\alpha} \tag{3}$$

- **Quality factor:** Remind that

$$Q_{\mathrm{TS}} = \frac{1}{\frac{1}{Q_{\mathrm{ES}}} + \frac{1}{Q_{\mathrm{MS}}}} \tag{4}$$

$$Q_{\mathrm{ES}} = \frac{R_{\mathrm{E}}}{Bl^2}\sqrt{\frac{M_{\mathrm{MS}}}{C_{\mathrm{MS}}}} \tag{5}$$

$$Q_{\mathrm{MS}} = \frac{1}{R_{\mathrm{MS}}}\sqrt{\frac{M_{\mathrm{MS}}}{C_{\mathrm{MS}}}} \tag{6}$$

  As a consequence, the electrical and mechanical quality factors of the loudspeaker (Q_{EC} and Q_{MC}, respectively) will increase:

$$Q_{\mathrm{EC}} = Q_{\mathrm{ES}}\sqrt{1+\alpha} \tag{7}$$

$$Q_{\mathrm{MC}} = Q_{\mathrm{MS}}\sqrt{1+\alpha} \tag{8}$$

  In addition, the total quality factor Q_{TC} will be also influenced by losses in the absorbent material and as well as by losses due to leakage. Therefore, the total quality factor is the joint contribution considering all the individual quality factors:

$$Q_{\mathrm{TC}} = \frac{1}{\frac{1}{Q_{\mathrm{EC}}} + \frac{1}{Q_{\mathrm{MC}}} + \frac{1}{Q_{\mathrm{A}}} + \frac{1}{Q_{\mathrm{L}}}} = \frac{1}{\frac{1}{Q_{\mathrm{TS}}\sqrt{1+\alpha}} + \frac{1}{Q_{\mathrm{A}}} + \frac{1}{Q_{\mathrm{L}}}} \tag{9}$$

  Although the losses due to Q_{A} and Q_{L} decrease the total quality factor Q_{TC}, the net effect of the closed box is to increase significantly Q_{TC} with respect to the total quality factor of the driver Q_{TS}. In closed boxes with damping material, Q_{A} is dominant over Q_{L}, so that the latter is usually neglected. Typical values for Q_{A} are around 5 in boxes with heavy filling, whereas $Q_{\mathrm{L}} \to \infty$.

- **Efficiency:** Remind that

$$\eta_0 = \frac{4\pi^2}{c^3} \frac{f_s^3 V_{AS}}{Q_{ES}} \tag{10}$$

Applying the changes introduced by the factor $(1+\alpha)$, the expression for η_0 remains unaltered:

$$\eta_0 = \frac{4\pi^2}{c^3} \frac{\left(f_s\sqrt{1+\alpha}\right)^3}{Q_{ES}\sqrt{1+\alpha}} \frac{V_{AS}}{1+\alpha} = \frac{4\pi^2}{c^3} \frac{f_s^3(1+\alpha)^{\frac{3}{2}}}{Q_{ES}(1+\alpha)^{\frac{3}{2}}} = \frac{4\pi^2}{c^3} \frac{f_s^3}{Q_{ES}}, \tag{11}$$

Therefore, the efficieny is uniquely determined by the transducer and not by the enclosure.

4.4 Loudspeaker performance

Together with V_B, three other parameters define the performance of a loudspeaker: lower cutoff frequency, flatness of the frequency response and maximum achievable SPL.

Low cutoff frequency: Let us define f_6 as the lower cutoff frequency at which sound pressure level decreases 6dB. This parameter explains at which extent the loudspeaker is able to reproduce low frequencies. For sealed enclosures, f_6 can be computed as:

$$f_6 = f_c \left(\frac{1}{6Q_{TC}^2} - \frac{1}{3} + \sqrt{\left(\frac{1}{6Q_{TC}^2} - \frac{1}{3}\right)^2 + \frac{1}{3}} \right)^{\frac{1}{2}} \tag{12}$$

Flatness of the frequency response: Increased Q_{TC} values are the cause of a low frequency boost in closed boxes, which compromises flatness in the frequency response. A way to measure flatness in closed boxes is by quantifying how much the LF peak exceeds the sound pressure level at the passband. With $Q_{TC} < 0.707$ the frequency response is flat, but for $Q_{TC} > 0.707$, this LF peak —expressed in dB— rises according to the following equation:

$$\text{LF peak} = 20\log_{10}\left(\frac{Q_{TC}^2}{\sqrt{(Q_{TC}^2 - 0.25)}}\right) \ \text{[dB]} \tag{13}$$

Table 3 gives the LF boost corresponding to different Q_{TC} values.

Q_{TC}	$\leq< 0.707$	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
LF peak [dB]	0	0.2	0.7	1.2	1.8	2.4	3.0	3.5	4.0

Table 3: LF peak or boost in closed boxes for different Q_{TC} values.

Maximum achievable SPL: How much SPL (referred at 1m) is able to output a loudspeaker whilst keeping linearity is an important performance parameter. Linearity is assumed as long as cone displacement is constrained below X_{max} (otherwise, exceeding X_{max} is a major cause of distortion). For a given input power, the extra stiffness of the air within the cabinet holds the diaphragm closer to its rest position, thus offering a valuable protection against cone displacement. The peak cone displacement depends therefore on α, among other parameters. From the analysis of the equivalent circuit it can be demonstrated that the peak displacement at 1W input power is:

$$X_{\text{peak@1W}} = \frac{C_{\text{MS}} Bl}{(1+\alpha)} \sqrt{\frac{2}{R_{\text{E}}}} \left[\frac{Q_{\text{TC}}^2}{\sqrt{Q_{\text{TC}}^2 - 0.25}} \right], \tag{14}$$

The term in brackets is related to cone displacement increase due to the effect of resonance. This term is equal to 1 for $Q_{\text{TC}} \leq$0.707 (which rarely occurs). From X_{max} and Equation 14, the maximum input power that satisfies the condition of linearity is:

$$P_{\text{E}_{\text{max}}} = \left(\frac{X_{\text{max}}}{X_{\text{peak@1W}}} \right)^2 \tag{15}$$

In order to avoid audible distortion, the input electrical power should not exceed this limit, besides the maximum power ratings specified by the transducer (maximum peak power can be considered as 4 times the nominal long-term power according to AES regulation) to prevent from thermal failure. Having determined the maximum input power, the maximum achievable SPL can be computed as:

$$SPL_{\text{max}} = 112.1 + 10 \log_{10} (\eta_0 P_{\text{E}_{\text{max}}}) \tag{16}$$

4.5 Alright, but which drivers are appropriate for closed-box designs?

Choosing an appropriate driver is one of the most important questions in loudspeaker design, and it is not simple at all. Actually, it depends on the target performance you aim to achieve, so the first step could be to fix the requirements of the box. If you are an unexperienced designer and are tempted to design a loudspeaker with a profound bass response (e.g. able to reach 30Hz) and achieve a high sound pressure level (e.g. 120dB SPL) in a pocket-size loudspeaker, just forget about it. That is not feasible at all, so you will have to decide which parameter(s) to prioritize. As you relax the requirements in one parameter you will be able to achieve better performance in the others.

For example, if the priority is focused on the frequency response, the key parameters of the driver are the resonance frequency and quality factors. Richard Small suggested a simple but effective rule based on the Efficiency Bandpass Product (EBP) that defined as:

$$\text{EBP} = \frac{f_{\text{s}}}{Q_{\text{ES}}} \tag{17}$$

He proposed that, in sealed enclosures, an extended bass response was only possible using drivers with low EBP values. In practice, he suggested EBP values close to 50Hz to achieve a great low-frequency response.

Otherwise, if the goal is to design a loudspeaker with compact dimensions, drivers with low V_{AS} should be prioritized. Finally, to achieve high SPL$_{\text{max}}$ values drivers with high efficiency (η_0), large linear excursions (X$_{\text{max}}$) and high power ratings (P_{E}) are usually required.

4.6 Example

To illustrate the process of closed-box design, let us take the driver SEAS L26RFX/P, with $f_s = 20$Hz, $Q_{ES} = 0.39$, $Q_{TS} = 0.33$, $V_{AS} = 171$l, $\eta_0 = 0.34$%, $X_{max} = 7$mm and $P_E = 125$W (AES). The first question to answer is: according to Small's criterion, do you think this is an appropriate transducer for closed-box design? From f_s and Q_{ES} it turns that $\mathrm{EBP} = 51$Hz, so the answer is affirmative. Subsequently, we will explore how the frequency response and cone excursion behaves with respect to α. For that, $\gamma = 1.2$, $Q_A = 5$ and $Q_L = \infty$ will be considered. Figure 5 represents the frequency response (left) and cone excursion (right) for $\alpha = 0$, 2, 5, 10 and 20. If you observe this figure you will appreciate how f_6 and the LF boost increase with α. On the other hand, cone displacement decreases with α.

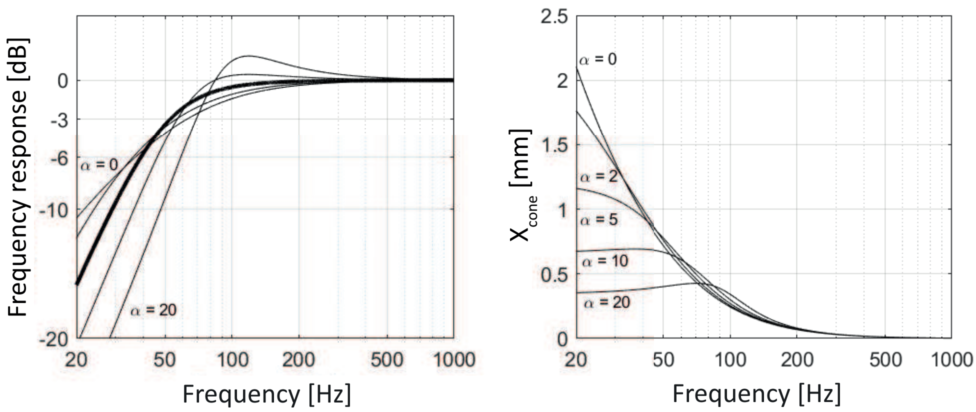

Figure 5: Frequency response (left) and cone displacement at 1W input power (right) for the SEAS L26RFX/P driver in sealed enclosures with α= 0, 2, 5, 10 and 20 and considering $Q_A = 5$ and $Q_L = \infty$.

Furthermore, Figure 6 illustrates graphically how the performance parameters of closed boxes vary with α. Notice that f_c and f_6 rise with α, consistently with Figure 5. The minimum reachable f_6 is 35Hz. However, to obtain such a low f_6, large box volumes (around 100l) are required. In addition, the low stiffness provided by large boxes causes large diaphragm excursions, even with low input power. As a result, low SPL values are achievable to keep excursions below X_{max} (in other words, to satisfy the linearity condition). Consequently, increasing the value of α is rather beneficial, since both V_B and SPL_{max} improve substantially, at the expense of increasing f_6 and the LF boost.

The question now is at which extent α could be reasonably increased. The answer lays in which f_6 and LF peak limits are acceptable. For example, let us now consider that we would accept f_6 to be at most as high as 50Hz and constraining the LF boost below 1.5dB. From Figure 6 we get that the condition for f_6 is satisfied for α values below 13, whereas the condition for the LF peak is satisfied whenever $\alpha < 17$. Accordingly, the most restrictive of these values (i.e. $\alpha = 13$) should be considered as the upper limit for α to satisfy our requirements. With $\alpha = 13$ the following performance parameters are obtained: $f_6 = 50$Hz, LF peak = 0.9dB, $V_B = 11$l and $\mathrm{SPL}_{max} = 109.7$dB. The maximum input power without exceeding X_{max} is about 150W. Although this value exceeds the nominal input power (P_E=125W), it should be remarked that P_E refers to long-term continuous average power. Therefore, the important issue to prevent speker damage is to keep the power handling of these peaks below the permissible peak power, which is 4 times P_E, as derived from the 6dB crest factor of the test signal, according to the current IEC standard, so that peaks of 150W can be perfectly handled without any concerns.

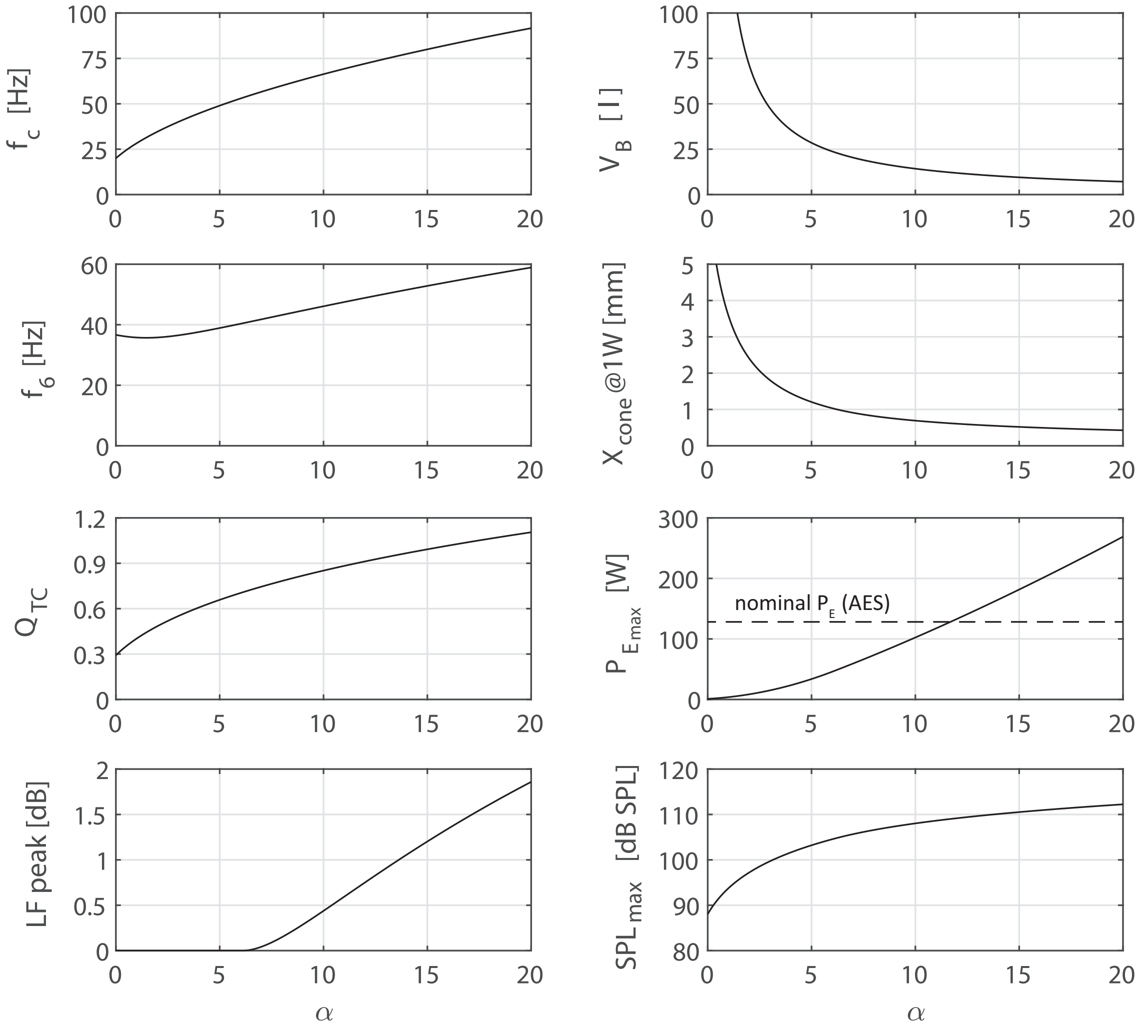

Figure 6: Performance evaluation of closed-box designs for the SEAS L26RFX/P driver as function of α and considering $Q_\mathrm{A} = 5$ and $Q_\mathrm{L} = \infty$.

5 Closing remarks

After reading this document you have the keys that govern the design of closed boxes. You are now able to identify wheter a driver is appropriate or not for sealed enclosures. For a given driver you can also determine the maximum α that provides a reasonable frequency response and SPL output keeping box size as compact as possible. Finally, from the parameters of the driver and the enclosure you can compute and specify the parameters that define the performance of a loudspeaker system.

References

[1] Leo L. Beranek and Tim J. Mellow. Acoustics: Sound Fields and Transducers. Elsevier Academic Press, 2012.

[2] Vance Dickason. Loudspeaker Design Cookbook 7th Edition. Segment LLC, 2005.

[3] John L. Murphy. Introduction to Loudspeaker Design. True Audio, 2014.