Closed-Box Design with a Given Driver

(From the book *Introduction to Electroacoustics and Audio Amplifier Design, Second Edition - Revised Printing*, by W. Marshall Leach, Jr., published by Kendall/Hunt, © 2001.)

The first step in designing a closed-box system for a given driver is to select the driver. The ones which give the best response have a very low resonance frequency. The next step is to measure the small-signal driver parameters. Manufacturers' test data should not be used unless the parameters cannot be measured. If two drivers are measured for a stereo system, it is not unusual for the parameters to differ by 10% to 15%. In this case, it is acceptable to average the parameters and base the system design on the averages. The parameters required for the design are f_S, V_{AS}, Q_{TS}, Q_{MS}, and Q_{ES}. The design procedure is as follows:

1. Specify the desired Q_{TC}. The driver must have a Q_{TS} that is lower than the desired Q_{TC}, otherwise it cannot be used. Q_{TC} should be selected in the range of 0.6 to 0.8 if the low-frequency response is to be optimized. A higher value results in a smaller enclosure which can be an important consideration if the system size matters.

2. Estimate the mechanical quality factor Q_{MC}. For a filled system, it is typical to guess the value $Q_{MC} = 3.5$. An often used rule of thumb for Q_{MC} is as follows:

$$\text{For Unfilled Systems: } 5 \leq Q_{MC} \leq 10 \qquad \text{For Filled Systems: } 2 \leq Q_{MC} \leq 5 \tag{1}$$

3. Calculate the electrical quality factor Q_{EC}, the compliance ratio α, and the effective acoustic box volume V_{AB}.

$$Q_{EC} = \frac{Q_{MC}Q_{TC}}{Q_{MC} - Q_{TC}} \qquad \alpha = \left(\frac{Q_{EC}}{Q_{ES}}\right)^2 - 1 \qquad V_{AB} = \frac{V_{AS}}{\alpha} \tag{2}$$

4. Calculate the fundamental resonance frequency $f_C = f_S\sqrt{1+\alpha}$. The lower half-power cutoff frequency f_ℓ is given by

$$f_\ell = f_C \left[\left(\frac{1}{2Q_{TC}^2} - 1\right) + \sqrt{\left(\frac{1}{2Q_{TC}^2} - 1\right)^2 + 1}\right]^{1/2} \tag{3}$$

The internal box volume V_B should be calculated to account for the effect of the filling. For a filled enclosure, V_B is smaller than V_{AB} by about 25%, i.e. $V_B \simeq V_{AB}/1.25$. To minimize standing waves inside the box, there are two sets of ratios of the internal dimensions that should be used. These ratios are

$$0.6 \times 1.0 \times 1.6 \qquad \text{and} \qquad 0.8 \times 1.0 \times 1.25 \tag{4}$$

The first ratios give a more rectangular shaped box while the second ratios give a more cubic shaped box. When the box is built, it must be properly braced inside. Allowance for the volume occupied by both the bracing and the drivers must be made. An empirical relation for the volume occupied by a woofer inside the box is

$$V_{\text{driver}} \simeq 6 \times 10^{-6} \times d^4 \quad \text{cubic feet} \tag{5}$$

where d is the advertised diameter of the driver in inches. For example, the volume occupied by a 12-inch driver is approximately 0.12 cubic feet.

Example 1 *A* 12-*inch driver has the parameters:* $f_S = 19$ *Hz,* $Q_{MS} = 3.7$*,* $Q_{ES} = 0.35$*, and* $V_{AS} = 19$ *feet*^{3}*. The voice-coil electrical power rating is* $P_{E(\max)} = 25$ *W, the peak linear voice-coil displacement is* $x_{\max} = 6$ *mm (1/4 inch), and the diaphragm piston radius is* $a = 0.12$ *m. (a) If* $Q_{MC} \simeq 3.5$*, calculate* V_{AB} *and* V_B *for* $Q_{TC} = 1/\sqrt{2}$*. Assume* $V_B = V_{AB}/1.25$*. (b) Calculate the lower half-power cutoff frequency* f_ℓ*. (c) Calculate the displacement limited maximum acoustic output power* $P_{AR(\max)}$*. (d) Calculate the efficiency* η_0 *and the corresponding electrical power input* P_E *required to achieve the maximum acoustic output power.*

Solution. (a) $Q_{EC} = Q_{MC}Q_{TC}/(Q_{MC} - Q_{TC}) = 0.89$, $\alpha = (Q_{EC}/Q_{ES})^2 - 1 = 5.47$, $V_{AB} = V_{AS}/\alpha = 3.47$ feet^3, $V_B = 3.47/1.25 = 2.78$ feet^3. (b) $f_C = \sqrt{1+\alpha} f_S = 48.3$ Hz. For the B2 alignment, the lower half-power cutoff frequency is equal to f_C so that $f_\ell = 48.3$ Hz. (c) The maximum volume of air that the diaphragm can displace is $V_{D(\max)} = x_{\max}\pi a^2 = 2.7 \times 10^{-4}$ m^3. The maximum displacement limited acoustic output power is

$$P_{AR(\max)} = \frac{4\pi^3 \rho_0 f_C^4}{c} V_{D(\max)}^2 \frac{Q_{TC}^2 - 0.25}{Q_{TC}^4} = 0.17 \text{ W} \tag{6}$$

(This expression is valid only for $Q_{TC} \geq 1/\sqrt{2}$. For $Q_{TC} < 1/\sqrt{2}$, the solution is the same as for $Q_{TC} = 1/\sqrt{2}$.) The system efficiency is

$$\eta_0 = \frac{4\pi^2}{c^3} \times \frac{f_C^3 V_{AT}}{Q_{EC}} = 0.010 \text{ or } 1\% \tag{7}$$

The electrical input power required to radiate $P_{AR(\max)}$ is $P_E = P_{AR(\max)}/\eta_0 = 17$ W. Because this is less than $P_{E(\max)}$, the system can deliver its maximum acoustic output power before electrical failure occurs.

Example 2 *Design the enclosure for the system of Example 1. Assume that the internal dimensions of the box have the ratios* $0.6 \times 1.0 \times 1.6$ *and that the box has bracing in each corner between all internal walls so that it forms a rectangular frame inside the box. The bracing has cross section dimensions of* 1.5 *inches by* 1.5 *inches (commonly called two-by-two bracing).*

Solution. Denote the internal width, height, and depth of the box, respectively, by w, h, and d. Let the height be the longest dimension and the depth be the shortest. Thus $w = h/1.6 = 0.625h$ and $d = 0.6w = 0.375h$. The volume occupied by the driver in the box is estimated to be 0.12 feet^3 so that the total internal volume of the unfilled box is $2.78 + 0.12 = 2.90$ feet^3. The volume occupied by each piece of bracing is equal to its cross-sectional area times its length. In cubic feet, this is given by $(1.5/12)^2 \times L$, where L is the length in feet. There are 12 bracing pieces. Let the 4 vertical pieces have a length equal to h. Thus 4 pieces are required having a length $w - 3/12$ feet and four pieces are required having a length $d - 3/12$ feet. The following equation can be written for the box height h:

$$\begin{aligned} 2.90 &= (0.625h) \times h \times (0.375h) - 4(1.5/12)^2 \times h - 4(1.5/12)^2 \times (0.625h - 3/12) \\ &\quad -4(1.5/12)^2 \times (0.375h - 3/12) = 0.234375h^3 - 0.1251h + 0.03125 \end{aligned} \tag{8}$$

This equation can be solved for h to obtain $h = 2.382$ feet. The width and depth are $w = h/1.6 = 1.489$ feet and $d = 0.6w = 0.8931$ feet.

System Verification

To verify a system design, any crossover network must be disconnected. The parameters f_C and Q_{TC} must be measured. These can be determined by the techniques described in *Introduction to Electroacoustics and Audio Amplifier Design*. The lower -3 dB frequency of the system can then be calculated from Eq. (3).