Loudspeaker Parameters

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Outline

• Review of How Loudspeakers Work
• Small Signal Loudspeaker Parameters
• Effect of Loudspeaker Cable
• Sample Loudspeaker
• Electrical Power Needed
• Sealed Box Design Example
How Loudspeakers Work

When the electrical current flowing through the voice coil changes direction, the coil’s polar orientation reverses. This changes the magnetic forces between the voice coil and the permanent magnet, moving the coil and attached diaphragm back and forth.

A current-carrying wire in a magnetic field experiences a magnetic force perpendicular to the wire.
How Loudspeakers Are Made

**BASKET**
This is the chassis of the drive unit to which all elements are attached and which itself bolts into the cabinet.

**MAGNET**
This is the motor of a loudspeaker - it provides the energy that causes the voice coil to move.

**POLE PIECES**
These focus the magnetic field so that it is strongest around the voice coil.

**SUSPENSION SPIDER & VOICE COIL**
The spider holds the voice coil central within the magnet and acts as a spring to bring it back after each pulse. The speaker cone is attached to the voice coil which sits in a magnetic field and moves when a signal passes through it. Variations in the signal make the coil vibrate the drive unit in a pistonic motion which produces sound by resonating airwaves in the room much like a drum.

**DRIVE CONE & SURROUND**
Many alternative materials have been used to make cone drivers for mid and low frequencies. Kevlar, paper, aluminium, and polypropylene are very popular choices.

**PHASE PLUG**
Not found on all drive units but designed to avoid phase changes. More commonly drive units feature a dust cap to stop dust entering the system.

**MOUNTING RING**
This cosmetic device hides the raw alloy of the basket when it’s mounted in the cabinet.
Fundamental Small Signal Mechanical Parameters

- \( S_d \) – projected area of driver diaphragm (m\(^2\))
- \( M_{ms} \) – mass of diaphragm (kg)
- \( C_{ms} \) – compliance of driver’s suspension (m/N)
- \( R_{ms} \) – mechanical resistance of driver’s suspension (N•s/m)
- \( L_e \) – voice coil inductance (mH)
- \( R_e \) – DC resistance of voice coil (\(\Omega\))
- \( B_l \) – product of magnetic field strength in voice coil gap and length of wire in magnetic field (T•m)
**Small Signal Parameters**

These values can be determined by measuring the input impedance of the driver, near the resonance frequency, at small input levels for which the mechanical behavior of the driver is effectively linear.

- $F_s$ – (free air) resonance frequency of driver (Hz)
  - frequency at which the combination of the energy stored in the moving mass and suspension compliance is maximum, which results in maximum cone velocity
  - usually it is less efficient to produce output frequencies below $F_s$
  - input signals significantly below $F_s$ can result in large excursions
  - typical factory tolerance for $F_s$ spec is ±15%
Measurement of Loudspeaker Free-Air Resonance
Small Signal Parameters

These values can be determined by measuring the input impedance of the driver, near the resonance frequency, at small input levels for which the mechanical behavior of the driver is effectively linear.

- $Q_{ts}$ – total Q of driver at $F_s$
  - unitless measurement, characterizing the combined electrical and mechanical damping of the driver
  - proportional to the energy stored, divided by the energy dissipated
  - most drivers have $Q_{ts}$ values between 0.2 and 0.5
Small Signal Parameters

These values can be determined by measuring the input impedance of the driver, near the resonance frequency, at small input levels for which the mechanical behavior of the driver is effectively linear.

- **$Q_{ms}$** – mechanical Q of driver at $F_s$
  - unitless measurement, characterizing the mechanical damping of the driver, i.e., losses in the suspension (surround and spider)
  - varies roughly between 0.5 and 10 (typical value is 3)
  - high $Q_{ms}$ indicates lower mechanical losses
  - main effect of $Q_{ms}$ is on impedance: high $Q_{ms}$ drivers display a higher impedance peak
Small Signal Parameters

These values can be determined by measuring the input impedance of the driver, near the resonance frequency, at small input levels for which the mechanical behavior of the driver is effectively linear.

- $Q_{es}$ – electrical Q of driver at $F_s$
  - a unitless measurement, describing the electrical damping of the speaker
  - as the coil of wire moves through the magnetic field, it generates a current which opposes the motion of the coil ("back EMF")
  - the back EMF decreases the total current through the coil near $F_s$, reducing cone movement and increasing impedance
  - $Q_{es}$ is the dominant factor in voice coil damping for most drivers (depends on amplifier output impedance)
Aside: How Does Loudspeaker Cable And Power Amplifier Output Impedance Affect Performance?

- Damping is a measure of a power amplifier's ability to control the back EMF motion of the loudspeaker cone after the signal disappears.
- The **damping factor** of a system is the ratio of the loudspeaker's nominal impedance to the total impedance driving it.
- Example: Amplifier with damping factor of 300 (bigger is better) driving an 8Ω load means that the output impedance is 0.027Ω (lower is better).
- Impedance of speaker cable used can significantly reduce the damping factor (larger gauge wire has lower impedance).
Line Loss

This calculator provides line loss with 2-conductor cable on a constant voltage line.

Equation used to calculate the data:

\[ P_{loss} = 10 \times \log \left( 1 - \frac{2 \times RL}{2 \times RL + (V_{line}^2 / Prate)} \right) \]
Small Signal Parameters

These values can be determined by measuring the input impedance of the driver, near the resonance frequency, at small input levels for which the mechanical behavior of the driver is effectively linear.

- \( V_{as} \) – equivalent compliance volume (volume of air which, when acted upon by a piston of area \( S_d \), has the same compliance as the driver’s suspension)
  - measure of the “stiffness” of the suspension with the driver mounted in free air
  - represents the volume of air that has the same stiffness as the driver’s suspension when acted upon by a piston of the same area \( S_d \) as the cone
  - larger values mean lower stiffness (and generally require larger enclosures)
  - \( V_{as} \) varies with the square of the speaker’s diameter
  - typical factory tolerance for \( V_{as} \) is \( \pm 20-30\% \)
Sample Loudspeaker

**Product Description**
- Aluminum cone
- Synthetic dust cap
- Rubber surround
- Stamped steel basket
- 1" copper voice coil
- 17.7oz. magnet

**Specifications:**
- Power Capacity: 50W/100W RMS/peak
- Sensitivity: 86dB (W/M)
- Impedance: 8Ω
- Re: 6.6Ω
- Le: 0.48mH
- Frequency response: 65Hz ~ 17KHz
- Fs: 65Hz
- Qts: 0.365
- Qes: 0.436
- Qms: 2.25
- Vas: 3.15 (liters)
- Xmax: 2.25mm
- Overall frame diameter: 4.13” (pincushion)
- Required cutout: 3.66”
- Mounting depth: 2.5”

**Sensitivity = 86 dB**
Fs = 65 Hz
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Aside: How Loud Does This Thing Get? (And, How Much Power Do I Need?)

- Relating electrical power needed to produce desired SPL at a given listening distance:
  - sensitivity rating of loudspeaker (typically spec as 1 m on-axis with input of 1 electrical watt)
  - acoustic level change/attenuation between loudspeaker and farthest listening position

- Example: want 90 dB program level at listening distance of 4 m outdoors (i.e., no reinforcement of sound due to room reflections)
  - loudspeaker sensitivity measured as 86 dB
  - acoustic level change = 20 log (4) ≈ 12 dB
  - SPL required at source is 90 + 12 = 102 dB
  - need 16 dB above 1 watt, or 10 \(^{(16/10)}\) = 40 W
  - check to make sure driver can handle it!
Amplifier Power Required

Equations used to calculate the data:

\[ dBW = L_{req} - L_{sens} + 20 \times \log \left( \frac{D_2}{D_{ref}} \right) + HR \]

\[ W = 10 \text{ to the power of } \left( \frac{dBW}{10} \right) \]

Where:

- \( L_{req} \) = required SPL at listener
- \( L_{sens} \) = loudspeaker sensitivity (1W/1M)
- \( D_2 \) = loudspeaker-to-listener distance
- \( D_{ref} \) = reference distance
- \( HR \) = desired amplifier headroom
- \( dBW \) = ratio of power referenced to 1 watt
- \( W \) = power required

This calculator provides the required electrical power (power output from the amplifier) to produce a desired Sound Pressure Level (SPL) at a given distance, along with an amount of headroom to keep the amplifier(s) out of clip.

Example: You are designing a system where the farthest listening position from the loudspeaker is 100 meters, and the desired Sound Pressure Level is 95 dB SPL. The loudspeaker chosen for the job has a sensitivity rating of 95 dB. With the minimum recommended amplifier headroom of 3 dB, then you need to choose an amplifier that can supply at least 1,995 watts to the loudspeaker.
Enclosure-Related Parameters

- **EBP = \( F_s / Q_{es} \)**
  - used loosely to decide what type of enclosure will be best for a given speaker ("rule of thumb")
  - sealed box EBP ≈ 50
  - vented enclosure EBP ≈ 100
- **\( F_c \)** = sealed enclosure resonance
- **\( V_c \)** = internal volume of a sealed enclosure
- **\( V_b \)** = internal volume of a vented enclosure
- **\( F_b \)** = bass reflex enclosure resonance
- **\( L_v \)** = length of port
- **\( Q_{tc} \)** – desired value determines size and type of enclosure
  - value of 0.707 is what most designers aim for (yields flattest response)
  - enclosures designed to enhance bass may range from 0.8 to 1.1 (bigger value, "boomier" sound)
  - enclosures that are too big (\( Q_{tc} < 0.707 \)) can sound "tinny"
Sealed Box
Sealed Box

- Theoretically an infinite baffle with an additional stiffness component added (to the existing suspension compliance) due to the springiness of the air volume trapped in the enclosure.

- A smaller box will have a greater stiffness contribution than a larger one – in sealed box systems the air restoring force is normally made dominant (compared with that of the driver suspension).
Electromechanical Equivalent for Driver in a Sealed Box

Simplified form – system response is that of a damped single-resonant circuit.
Response Shape

- Critically damped ($Q_{TC} = 0.5$): response is -6 dB at resonance (no ringing/overshoot in transient response)
- Butterworth alignment ($Q_{TC} = 0.7$): response is -3 dB at resonance (response is “maximally flat” and has good transient behavior)
- $Q_{TC} = 1$: provides greater bandwidth at expense of transient response accuracy
- Chebychev alignment ($Q_{TC} = 1.1$): 2 dB peak in response at resonance – results in optimum efficiency alignment for a sealed box system, and is permissible for a small system of limited bandwidth (e.g., $F_c$ of 65 Hz and above)
Behavior of a Closed-Box Loudspeaker System for Several Values of Total System $Q_{TC}$

- **Amplitude vs. Normalized Frequency Response**
  - Sound pressure (dB)
  - Normalized frequency, $f/f_c$
  - Curves for $Q_{TC} = 2.0$, 1.4, 1.0, 0.71, 0.50

- **Normalized Step Response**
  - Time, $t/2\pi T_c$
  - Curves for $Q_{TC} = 0.50$, 0.71, 1.0, 1.3, 1.6, 2.0
Enclosure Volume and Efficiency

- The maximum efficiency even a large sealed-box enclosure can achieve is small (1-2%)
- Increasing the box cutoff frequency increases the theoretical efficiency
- The closed-box system efficiency in the passband region (system reference efficiency) is the reference efficiency of the driver operating with the particular value of air-load mass provided by the system enclosure
- Reference efficiency ($\eta_0$) calculation:

$$\eta_0 = \frac{4\pi^2}{c^3} \times \frac{(F_S^3 V_{AS})}{Q_{ES}} = \frac{4\pi^2}{c^3} \times \frac{(F_C^3 V_{AT})}{Q_{EC}}$$

where $V_{AT}$ is a volume of air having the same total acoustic compliance as the driver suspension and enclosure acting together
Relationship of Maximum Reference Efficiency to Cutoff Frequency and Enclosure Volume

Example: An 8 cu. ft. (e.g. 2'x2'x2') sealed box with a reference efficiency ($\eta_0$) of 2% would have a cutoff frequency ($F_c$) of slightly less than 40 Hz

Chart for Chebychev Alignment
Box Filling or Damping

- Stuffing may offer an apparent air volume increase of up to 15%.
- Additionally, stuffing may add a mass component due to physical movement of the filling at lower frequencies.
- Combined effects lower the system resonance and must be accounted for in the design (the effective cone mass increase could be as much as 20%).
- Very dense fillings will increase frictional air losses in the enclosed air volume and augment the damping.
- If system is designed correctly, such damping is not required, but may help control a system where the $Q_{TC}$ is too high (e.g., due to inadequate magnet strength).
- Movement of the filling is undesirable!
Sealed Box Design

• Compliance Ratio: \( \alpha = \frac{V_{AS}}{V_B} \)

• System-driver relationships:
  \[
  \frac{Q_{TC}}{Q_{TS}} \approx \frac{Q_{EC}}{Q_{ES}} = \frac{F_C}{F_S} = (\alpha + 1)^{0.5}
  \]
  \[
  \frac{F_C}{Q_{TC}} \approx \frac{F_S}{Q_{TS}} \text{ where } Q_{TS} \text{ is the total } Q \text{ of the driver at } F_S \text{ for zero source resistance, i.e.}
  \]
  \[
  Q_{TS} = \frac{Q_{ES}Q_{MS}}{(Q_{ES} + Q_{MS})}
  \]

• These equations show that for any enclosure-driver combination the speaker resonance frequency must always be lower than that of the system resonance frequency (i.e., value of \( \alpha \)) and \( Q \) will be in the same ratio as those of the driver, but individually raised by a factor of \((\alpha+1)^{0.5}\)

• Provides guidance for both “fixed driver” designs and designs where only a final system specification is given
Ratio of Closed-Box System Resonance Frequency \( (F_C) \) and Total Q \( (Q_{TC}) \) to Driver Resonance Frequency \( (F_S) \) and \( Q_T \), as a Function of the System Compliance Ratio \( (\alpha) \)

\[ f_C = \text{box cutoff frequency} \]

\[ f_S = \text{loudspeaker free-air resonance frequency} \]

Compliance Ratio: \( \alpha = \frac{V_{AS}}{V_B} \)
Sealed Box Design Example

- \( F_S = 31 \text{ Hz} \)  
  - \( \text{EBP} = 40 \rightarrow \text{use sealed enclosure} \)
- \( Q_{ES} = 0.77 \)
- \( Q_{MS} = 1.89 \)
- \( V_{AS} = 65.8 \text{ liters} \)
- \( \eta_0 = \frac{4\pi^2}{c^3} \times \frac{F_S^3 \times V_{AS}}{Q_{ES}} \)
  - \( = \left(9.64 \times 10^{-7}\right) \times \left(31^3 \times 65.8\right)/0.77 = 2.45\% \)
- effective diaphragm radius = 10.2 cm (0.102 m), giving \( S_D = 3.27 \times 10^{-2} \text{ m}^2 \)
- peak linear displacement (\(X_{\text{max}}\)) given as 3.8 mm (3.8 \times 10^{-3} \text{ m})
- peak displacement volume = \( V_D = S_D \times X_{\text{max}} = 1.24 \times 10^{-4} \text{ m}^3 \) (124 cm\(^3\))
- power rating given as 70W RMS
Sealed Box Design Example

• constraints
  – driver resonance frequency ($F_S$) must always be lower than that of the system ($F_C$)
  – $\alpha$ must be at least 3
  – $Q_{TS}$ must be lower than highest acceptable $Q_{TC}$
  – $V_{AS}$ must be at least several times larger than the enclosure size (volume)
  – select most desirable combination of $F_C$ and $Q_{TC}$ that satisfies $F_C / Q_{TC} \approx F_S / Q_{TS}$ and then calculate $\alpha = V_{AS} / V_B$

• calculations
  – $Q_{TS} = (0.77)(1.89)/(0.77+1.89) = 0.547$
  – based on $\alpha \geq 3$ requirement, $F_C/F_S \geq 2 \rightarrow F_C \geq 62$
  – $F_S / Q_{TS} = 56.7 \approx F_C / Q_{TC} \rightarrow$ for $F_C = 62$ get $Q_{TC} \approx 1.1$ ("Chebychev Alignment" → maximum efficiency)
  – internal volume of box needed based on $\alpha$
    $\alpha = V_{AS} / V_B$ (want $\alpha \geq 3$) $\rightarrow V_B \leq 22$ liters (0.022 m$^3$)
  – yields approximate size of: 0.28 m x 0.28 m x 0.28 m
Speaker Parameters:
- Qtc: 1.1
- Qts: 0.55
- Qes: 0.77
- Fs: 31 Hz
- Vas: 65.8 liters
- Pmax: 70 watts
- Diameter: 20.32 cm
- Xmax: 3.8 mm

Box Results:
- Vb: 21.9333 liters
- Fb: 62 Hz
- F3: 46.9183 Hz

Frequency Response: Output vs. Frequency
Vented Box Design Example

- alignments (choice depends on $Q_{ts}$)
  - QB3 – quasi 3rd order Butterworth
  - SBB4 – 4th order Butterworth ("maximally flat")
  - C4 – 4th order Chebychev
- need to determine port size/length