Week 9: The sealed cabinet loudspeaker

Microphone and Loudspeaker Design - Level 5

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A weekly fact about Salford

Did you know...

- Salford as a settlement dates back to the Early Middle Ages originally named *Sealhford*, meaning "ford by the willows". In the Domesday Book of 1086 the Hundred of Salford was recorded as covering an area of 350 square miles (906 km2) with a population of 35,000. Manchester was recorded as within the hundred of Salford.

What are we covering today?

1. Sealed cabinet equivalent circuit
2. Sealed cabinet analysis
3. Sealed cabinet design: choosing an alignment
4. Sealed cabinet geometry
5. Cabinet damping

Sealed cabinet equivalent circuit

Sealed cabinet loudspeaker: the OG

- We are ready to consider our first *practical* loudspeaker system - **the sealed cabinet**
- Infinite baffle is impractical to make... Can be approximated by a large sealed cabinet.
- 1944 - 'Invented' in by Olsen and Preston
- 1950s - Became popular in Hi-Fi
- 1972 - R. Small publishes papers on how to design a sealed cabinet (Part 1, Part 2)

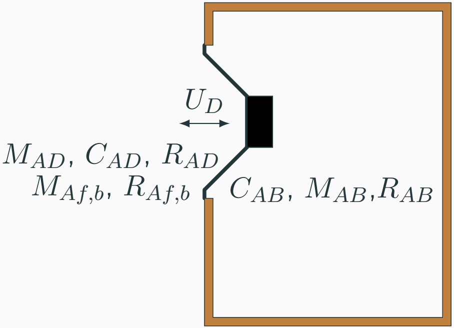

Figure 1: Sealed cabinet loudspeaker.

- We want to use equivalent circuit theory to design a sealed cabinet...

Sealed cabinet loudspeaker: the OG

- Sealed cabinet introduces a complex load on the rear of driver

$$Z_{Ab} = \overbrace{R_{Ab} + j\omega M_{Ab}}^{\text{Air loading}} + \underbrace{R_{AB} + j\omega M_{AB} + \frac{1}{j\omega C_{AB}}}_{\text{Cabinet loading}} \tag{1}$$

- For a small cabinet volume compliance is dominant

$$\frac{1}{j\omega C_{AB}} = \frac{\rho_0 c^2}{j\omega V_B} >> j\omega M_{AB} \tag{2}$$

- Resistance due to cavity damping is difficult to quantify - **we will assume a lossless cavity** (for now...)

Sealed cabinet loudspeaker: acoustic loading

- Cabinet loading reduces to just an additional compliance

$$Z_{Ab} = R_{Ab} + j\omega M_{Ab} + \cancel{R_{AB}} + \cancel{j\omega M_{AB}} + \frac{1}{j\omega C_{AB}} \tag{3}$$

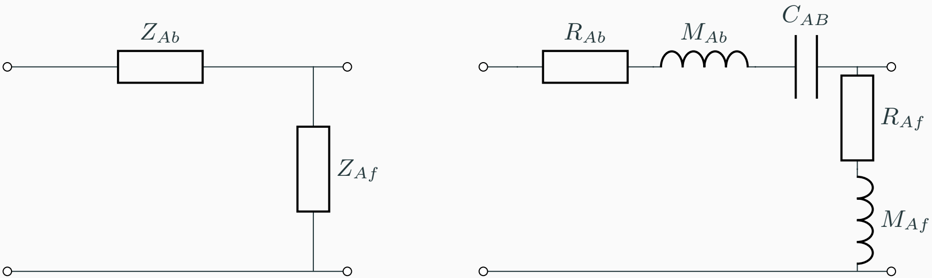

Figure 2: Equivalent circuit loading for lossless sealed cabinet.

Sealed cabinet loudspeaker: complete circuit

- Complete equivalent circuit for a sealed cabinet loudspeaker.
- Group terms and simplify...

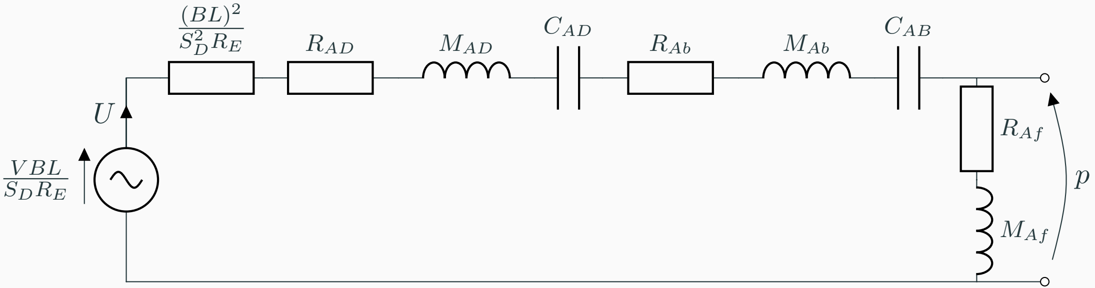

Figure 3: Complete equivalent circuit for lossless sealed cabinet.

Sealed cabinet loudspeaker: simplified circuit

- Sealed cabinet has negligible effect on acoustic mass and damping

$$M_{AT} \approx M_{AS} = M_{AD} + 2M_{Af} \quad (4)$$

$$R_{AT} \approx R_{AS} = \frac{(BL)^2}{S_D^2 R_E} + R_{AD} + 2R_{Af} + \cancel{R_{AB}} \quad (5)$$

- Total compliance given by *two series capacitors*

$$C_{AT} = \frac{C_{AD} C_{AB}}{C_{AD} + C_{AB}} \quad (6)$$

- Circuit is very similar to infinite baffle, only difference is C_{AT}

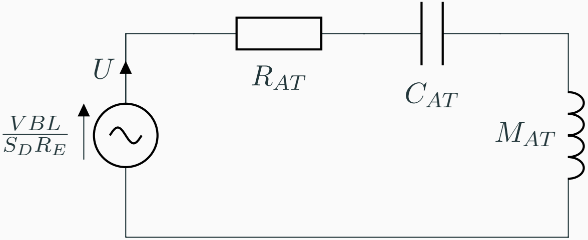

Figure 4: Complete equivalent circuit for lossless sealed cabinet.

Sealed cabinet loudspeaker: resonance and Q-factor

- Volume velocity has the same form as infinite baffle

$$U = \frac{VBL}{S_D R_E} \frac{1}{\left(j\omega M_{AT} + \frac{1}{j\omega C_{AT}} + R_{AT}\right)} = \frac{VBL}{S_D R_E j\omega M_{AT}} \frac{1}{\left(1 + \frac{\omega_c}{j\omega} \frac{1}{Q_{TC}} - \frac{\omega_c^2}{\omega^2}\right)} \quad (7)$$

- Sealed cabinet resonance

$$\omega_c = \sqrt{\frac{1}{M_{AT} C_{AT}}} \neq \omega_s \quad (8)$$

- Sealed cabinet Q-factor

$$Q_{TC} = \frac{\omega_c M_{AT}}{R_{AT}} \neq Q_{TS} \quad (9)$$

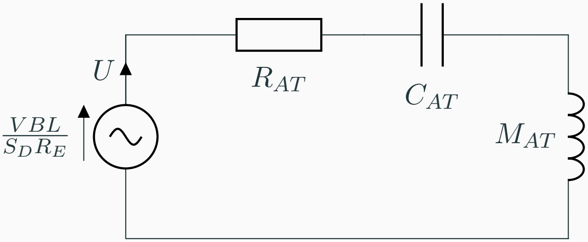

Figure 5: Complete equivalent circuit for lossless sealed cabinet.

Sealed cabinet loudspeaker: resonance and Q-factor

- For a **lossless sealed cabinet** loudspeaker we have,

$$Q_{TC} = \frac{\omega_c M_{AT}}{R_{AT}} \tag{10}$$

- For an **infinite baffle** loudspeaker we have

$$Q_{TS} = \frac{\omega_s M_{AS}}{R_{AS}} \tag{11}$$

- Recall that $M_{AT} \approx M_{AS}$ and $R_{AT} \approx R_{AS}$, so we have

$$\frac{Q_{TC}}{\omega_c} \approx \frac{Q_{TS}}{\omega_s} \tag{12}$$

- This is a **key design equation** for a lossless sealed cabinet loudspeaker!

Sealed cabinet analysis

Sealed cabinet: volume velocity

- Same procedure as infinite baffle!
- Diaphragm volume velocity made up of two parts:

$$U = \underbrace{\frac{VBL}{S_D R_E j\omega M_{AT}}}_{\text{First order LPF}} E(j\omega) \qquad (13)$$

$$E(j\omega) = \overbrace{\frac{1}{\left(1 + \frac{\omega_c}{j\omega}\frac{1}{Q_{TC}} - \frac{\omega_c^2}{\omega^2}\right)}}^{\text{Second order HPF}} \qquad (14)$$

- What about the radiated pressure?

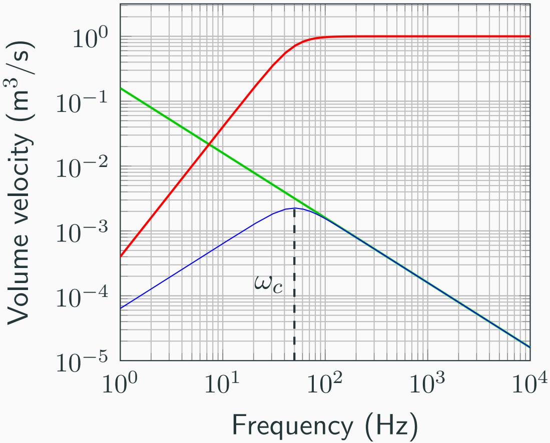

Figure 6: First and second order LPF/HPF terms in volume velocity

Sealed cabinet: radiated pressure

- Recall piston radiation:

$$p(r,t) = \frac{j\rho_0 ck}{4\pi r} U(\omega) \times \mathrm{DF}(\,) \qquad (15)$$

- Substitute in volume velocity:

$$U = \frac{VBL}{S_D R_E j\omega M_{AT}} E(j\omega) \qquad (16)$$

- **CANCELLATION**

$$p(r,t) = \frac{\cancel{j\omega}\rho_0}{4\pi r} \frac{VBL}{S_D R_E \cancel{j\omega} M_{AT}} E(j\omega) \qquad (17)$$

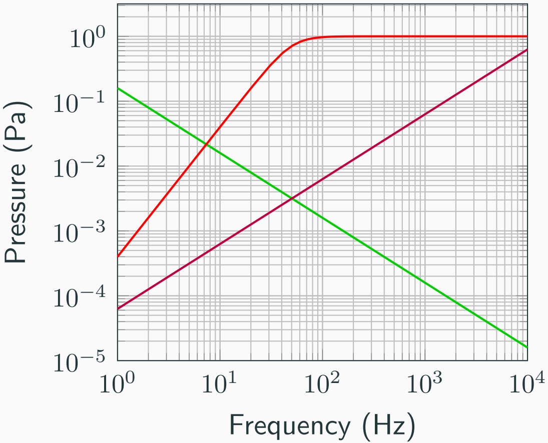

Figure 7: Radiated pressure terms

Sealed cabinet: radiated pressure

- Radiated pressure response

$$p(r,t) = \frac{\rho_0 VBL}{4\pi r S_D R_E M_{AT}} E(j\omega) \quad (18)$$

- Freq. dependence dictated by $E(j\omega)$:

$$E(j\omega) = \frac{1}{\left(1 + \frac{\omega_c}{j\omega}\frac{1}{Q_{TC}} - \frac{\omega_c^2}{\omega^2}\right)} \quad (19)$$

- Controlled by ω_c and Q_{TC}.

- Remaining terms describe sensitivity (i.e. pass-band level)

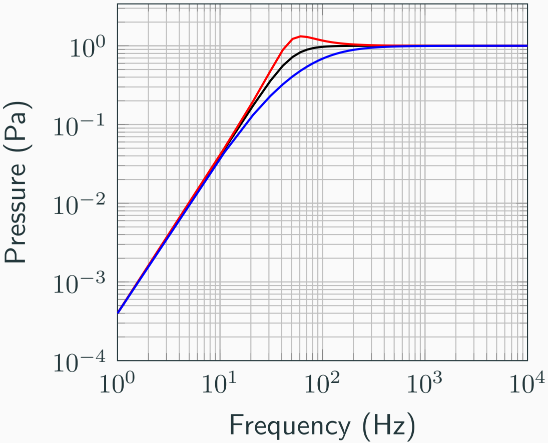

Figure 8: Example radiated pressure.

Sealed cabinet vs. infinite baffle

- So, how does the cabinet effect the radiated pressure?
- Added compliance alters ω_c,

$$\omega_c = \sqrt{\frac{1}{\frac{C_{AD}C_{AB}}{C_{AD}+C_{AB}} M_{AT}}} \qquad (20)$$

- The total compliance always less than driver $C_{AT} < C_{AD}$ - so sealed cabinet resonance always greater than infinte baffle $\omega_c > \omega_s$.

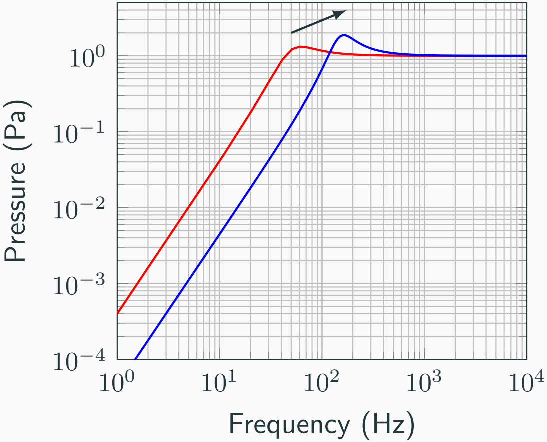

Figure 9: Example radiated pressure.

Sealed cabinet design: choosing an alignment

Sealed cabinet: model limitations

- Before using any model - **be aware of limitations**
- Model predicts reference region - where $E(j\omega) = 1$ - flat radiated pressure
- This does not extend up to 20 kHz
  - Coil inductance comes into play at HF
  - Piston radiation approx. valid $ka << 1$
  - Lumped param. assump. breaks down
- Use model to design **low frequency response only** - but that's okay!

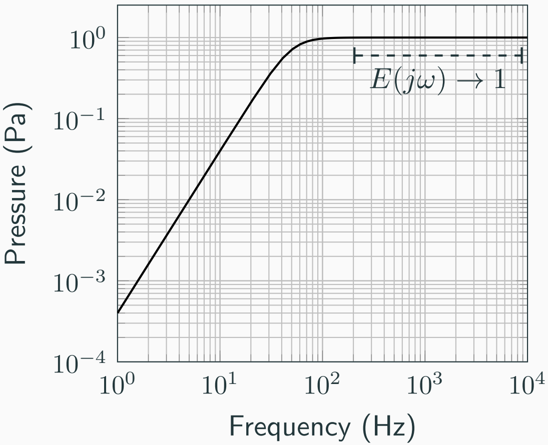

Figure 10: Example radiated pressure.

Sealed cabinet: design parameters

- Frequency response shape controlled by two parameters: ω_c and Q_{TC}
- Maximally flat response $Q_{TC} = 0.707$ - so called Butterworth alignment
- $Q_{TC} > 0.707$ - increasing bass boost
- $Q_{TC} < 0.707$ - slower roll-off
- When designing a sealed cabinet, we define Q_{TC} and solve for ω_c and V_B

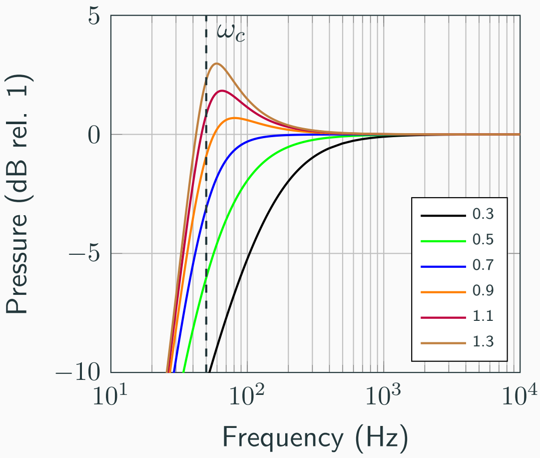

Figure 11: Example radiated pressure.

Sealed cabinet: Q-factor

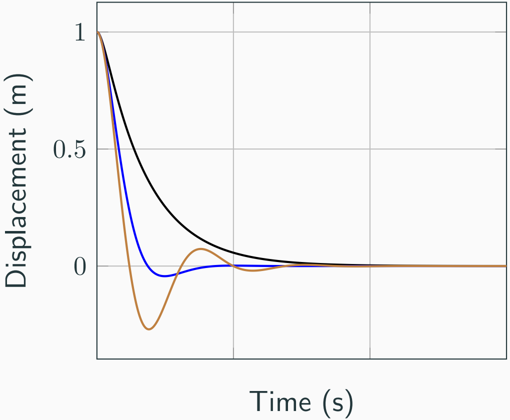

Figure 12: Transient response.

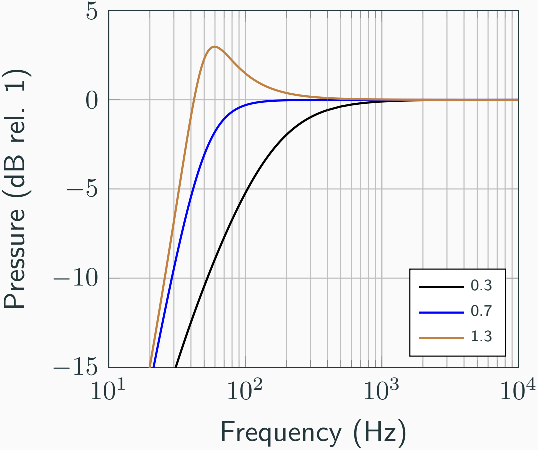

Figure 13: Frequency response.

Sealed cabinet geometry

Sealed cabinet: finding volume

- Volume of the cabinet V_B controls the compliance C_{AB}

$$C_{AB} = \frac{V_B}{\rho_0 c^2} \tag{21}$$

- This dictates the total compliance C_{AT}, which sets the sealed cabinet resonance ω_c

$$C_{AT} = \frac{C_{AD} C_{AB}}{C_{AD} + C_{AB}} \qquad \omega_c = \sqrt{\frac{1}{M_{AT} C_{AT}}} \tag{22}$$

- For a **lossless** sealed cabinet we also have the equation

$$\frac{Q_{TC}}{\omega_c} \approx \frac{Q_{TS}}{\omega_s} \qquad \to \qquad \omega_c \approx \frac{Q_{TC}}{Q_{TS}} \omega_s \tag{23}$$

- We use this equation to **find the sealed cabinet resonance** ω_c that gives Q_{TC}

Sealed cabinet: finding volume

- For a **lossless** sealed cabinet we have

$$\omega_c \approx \frac{Q_{TC}}{Q_{TS}} \omega_s \tag{24}$$

- Once ω_c is known, we can solve for the cabinet volume

$$V_B = C_{AB} \rho_0 c^2 \quad \leftarrow \quad C_{AB} = \frac{C_{AD} C_{AT}}{C_{AD} - C_{AT}} \quad \leftarrow \quad C_{AT} = \frac{1}{M_{AT} \omega_c^2} \tag{25}$$

- Design example:
  - Driver parameters: $d = 165$ mm, $f_s = 45$ Hz, $Q_{TS} = 0.65$, $M_{MS} = 11$ g
  - System parameters: $Q_{TC} = 0.9$, $f_c = ??$ Hz
  - Cabinet parameters: $V_B = ??$ m^3 (or L)

Sealed cabinet: effect of volume

- Ratio of infinite baffle and sealed cabinet resonance

$$\frac{\omega_c}{\omega_s} = \frac{\sqrt{\frac{1}{C_{AT}M_{AS}}}}{\sqrt{\frac{1}{C_{AS}M_{AS}}}} = \sqrt{\frac{C_{AS}}{C_{AT}}} \tag{26}$$

- Substitute total compliance

$$\frac{\omega_c}{\omega_s} = \sqrt{\frac{C_{AS}(C_{AS}+C_{AB})}{C_{AS}C_{AB}}} = \sqrt{1+\frac{C_{AS}}{C_{AB}}} \tag{27}$$

- Equivalently, in terms of volumes,

$$\frac{\omega_c}{\omega_s} = \sqrt{1+\frac{C_{AS}}{C_{AB}}} = \sqrt{1+\frac{V_{AS}}{V_B}} \tag{28}$$

- Increasing V_B, we get that $\omega_c \to \omega_s$ (infinite baffle limit!)

Sealed cabinet: effect of volume

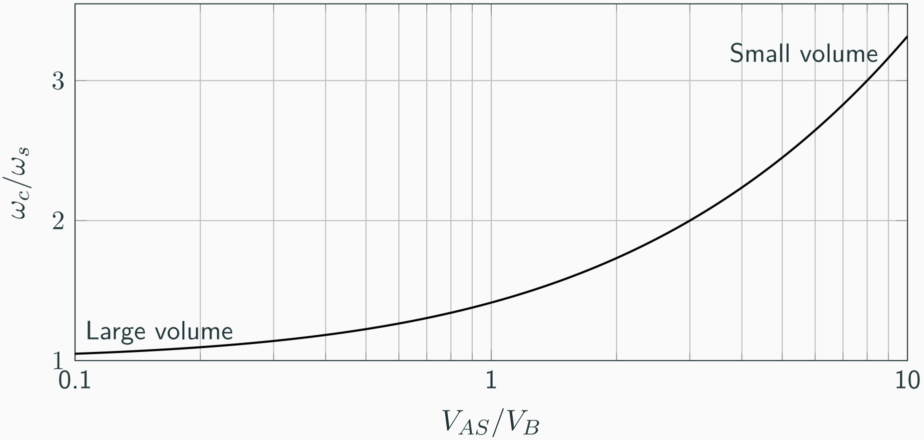

Figure 14: Effect of volume on cut off frequency.

Sealed cabinet: preferred dimensions

- The volume $V_B = L \times W \times H$ dictates the cabinet compliance. Any number of cabinet dimensions can be used to obtain the same volume. What should we use?
- Naive choice - set $L = W = H = \sqrt[3]{V_B}$ to get a square box.
  - **Problem:** degenerate modes!
  - Internal cabinet resonances can cause audible effects (lumps in the frequency response)
- Cavity modes occur at frequencies related to cabinet dimensions

$$f_{n_L, n_W, n_H} = \frac{c}{2\pi}\sqrt{\left(\frac{n_L \pi}{L}\right)^2 + \left(\frac{n_W \pi}{W}\right)^2 + \left(\frac{n_H \pi}{H}\right)^2} \tag{29}$$

- To avoid multiple modes occurring at same frequency we need to pick carefully W, L and H. **But how?**

Sealed cabinet: preferred dimensions

- This question has received lots of attention in field - relates also to room acoustics.
- There are a number of preferred ratios ($\text{dim}_1 : \text{dim}_2 : \text{dim}_3$):

  Golden ratio - $0.618 : 1 : 1.618$

  Bolt - $1 : 1.25 : 1.6$

  Louden - $1 : 1.4 : 1.9$
- To get cabinet geometry we set $\text{dim}_2 = \sqrt[3]{V_B}$ and solve for dim_1 and dim_3

$$\text{dim}_1 = \frac{\text{dim}_1}{\text{dim}_2}\text{dim}_2 \qquad \text{dim}_3 = \frac{\text{dim}_3}{\text{dim}_2}\text{dim}_2 \tag{30}$$

- For example, with $V_B = 0.1$ using golden ratio:

$$W = \sqrt[3]{0.1} = 0.464\text{m} \qquad L = 1.618 \times 0.464 = 0.751\text{m} \qquad H = 0.618 \times 0.464 = 0.287\text{m} \tag{31}$$

$$V_B = 0.464 \times 0.751 \times 0.287 = 0.1\text{m}^3 \tag{32}$$

Sealed cabinet: other considerations

- To prevent box being too large compliance ratio $\alpha = C_{AS}/C_{AB}$ should be 3-10
  - The compliance ratio should be more than 3, this ensures that the size of the box is not too large
  - The compliance ratio should be less than 10, this ensures that the mechanical suspension is not too compliant (a very compliant/flexible suspension gives us a large α). If the suspension is too compliant the system might become mechanically unstable.

- Driver resonance f_s should be less than half system resonance f_c

- Efficiency-bandwidth product: $\text{EBP} = f_s/Q_{TS}$
  - $\text{EBP} < 50$ better for sealed cabinet
  - $\text{EBP} > 100$ better for vented cabinet
  - In-between, could be used for either

Sealed cabinet: other considerations

- Cabinet panels exhibit resonances which can further colour the loudspeaker response
- To minimise panel resonance cabinets should be made as stiff as possible
  - Use reasonably heavy weight materials (e.g. 1/2 inch plywood)
  - Use internal bracing to stiffen cabinet

- **Can you think of any other considerations?**

Sealed cabinet: other considerations

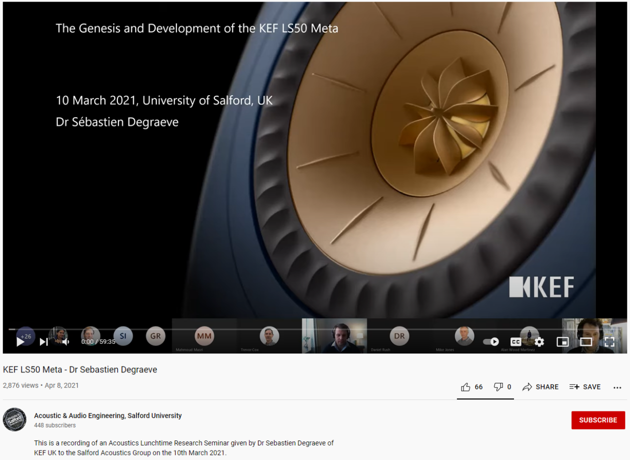

Figure 15: Click here to watch our KEF seminar!.

Cabinet damping

Cabinet damping: why bother?

- When the wavelength is an integer multiple of a cabinet dimension we get cavity modes=
- Cavity modes can cause unwanted fluctuations in the frequency response
- Their influence can be reduced by adding damping/absorption in the cabinet (just like in room acoustics)

- **Problem:** added damping also effects the frequency response of the loudspeaker - it changes the Q-factor and resonance frequency
- So, how do we design a loss sealed cabinet?

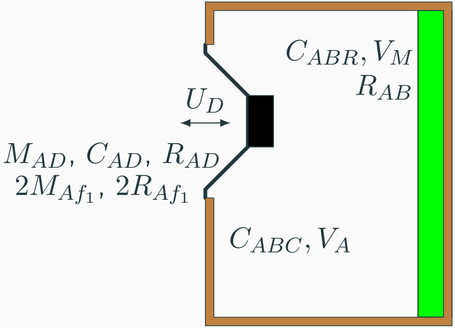

Figure 16: Sealed cabinet loudspeaker with added damping.

Sealed cabinet: apparent volume

- Adding absorbent material in the cavity increases the *apparent volume*
- Compliance of a volume is determined by its volume and the bulk modulus of air

$$C_{AB} = \frac{V_B}{\rho_0 c^2} = \frac{V_B}{\gamma P_0} \tag{33}$$

- Gaseous compressions are usually adiabatic (no exchange of heat) - if you add porous material compressions become isothermal
  - Speed of sound decreases - e.g. in Cellufoam it decreases from 344.8 to 292 m/s.
  - Compliance increases - volume appears larger than in adiabatic conditions
- Specific heat ratio γ reduces from 1.4 in adiabatic conditions to 1 in isothermal conditions

Cabinet damping: equivalent circuit loading

- Added cavity damping alters the load on the rear of the driver
- Z_{AB} represents the impedance due to the cabinet (i.e. not including air loading)
- Assume impedance due to air loading same as un-baffled so: $Z_{Af} + Z_{Ab} = 2Z_{Af}$

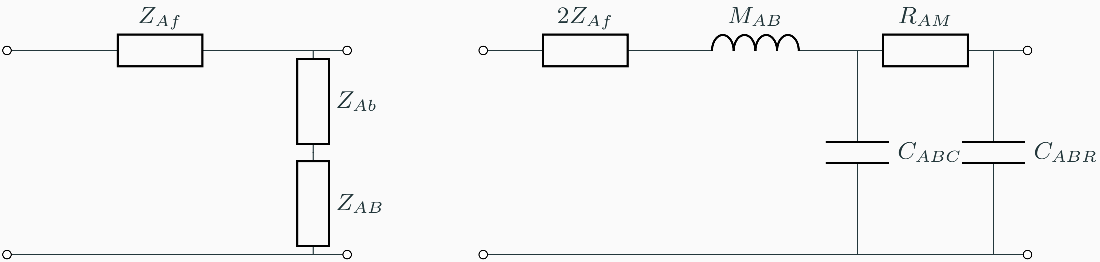

Figure 17: Equivalent circuit loading for lossless sealed cabinet.

Cabinet damping: dual compliances

- Rear load on loudspeaker due to cabinet

$$Z_{AB} = R_{AB} + \cancel{j\omega M_{AB}} + \frac{1}{j\omega C_{AB}} \tag{34}$$

- We again assume that box adds no additional mass ($M_{AT} \approx M_{AS}$), and for a lossy box $R_{AB} \neq 0$ and $C_{AB} = C_{ABC} + C_{ABR}$ (capacitors in parallel, can ignore R_{AM})

$$C_{ABC} = \frac{V_A}{\gamma P_0} \qquad C_{ABR} = \frac{V_M}{P_0} \qquad \frac{1}{j\omega C_{AB}} \approx \frac{1}{j\omega(C_{ABC} + C_{ABR})} \tag{35}$$

- Damping in the cavity has resistance $R_{AM} = dR_f/3S_M$ where R_f is flow resistivity and S_M is material area, and d is the material depth - what about R_{AB}?

Cabinet damping: apparent volume

- Find cavity damping R_{AB} by taking real part of Z_{AB}

$$R_{AB} = \text{real}\,(Z_{AB}) = \frac{R_{AM}}{\left(1 + \frac{C_{ABC}}{C_{ABR}}\right)^2 + \omega^2 R_{AM}^2 C_{ABC}^2} \tag{36}$$

- Net compliance C_{AB} gives the *'apparent'* volume V_{AB}

$$C_{AB} = C_{ABC} + C_{ABR} \qquad \rightarrow \qquad \frac{V_{AB}}{\gamma P_o} = \frac{V_A}{\gamma P_o} + \frac{V_M}{P_o} \tag{37}$$

- The **physical** cabinet volume is smaller than the apparent and is given by,

$$V_{AB} = V_A + \gamma V_M \qquad > \qquad V_B = V_A + V_M \tag{38}$$

Cabinet damping: so what's changed?

- Total acoustic mass, compliance and damping

$$M_{AT} = M_{AD} + M_{Af} + M_{Ab} + \cancel{M_{AB}} \tag{39}$$

$$C_{AT} = \frac{C_{AS}C_{AB}}{C_{AS} + C_{AB}} \qquad C_{AB} = C_{ABC} + C_{ABR} \tag{40}$$

$$R_{AT} = \frac{(BL)^2}{S_D^2 R_E} + R_{AD} + R_{Af} + R_{Ab} + R_{AB} \tag{41}$$

- As for lossless cabinet, the resonance frequency has the form

$$\omega_c = \sqrt{\frac{1}{M_{AT}C_{AT}}} \tag{42}$$

- How does this compare to the infinite baffle driver?

Cabinet damping: so what's changed?

- Infinite baffle resonance

$$\omega_s = \sqrt{\frac{1}{M_{AS}C_{AS}}} \tag{43}$$

- Sealed cabinet resonance

$$\omega_c = \sqrt{\frac{1}{M_{AT}C_{AT}}} = \sqrt{\frac{C_{AS}+C_{AB}}{M_{AT}C_{AS}C_{AB}}} \tag{44}$$

- Their ratio (assuming $M_{AS} \approx M_{AT}$) describes shift due to damping

$$\frac{\omega_c}{\omega_s} = \frac{\sqrt{\frac{C_{AS}+C_{AB}}{M_{AS}C_{AS}C_{AB}}}}{\sqrt{\frac{1}{M_{AS}C_{AS}}}} = \sqrt{1+\frac{C_{AS}}{C_{AB}}} = \sqrt{1+\frac{V_{AS}}{V_{AB}}} \tag{45}$$

- What about the Q-factor(s)..?

Cabinet damping: more Q-factors..?!

- Q-factor of speaker,

$$Q_{TS} = \frac{1}{R_{AS}}\sqrt{\frac{M_{AS}}{C_{AS}}}, \qquad R_{AS} = \frac{(BL)^2}{S_D^2 R_E} + R_{AD} + R_{Af} + R_{Ab} \tag{46}$$

- Total Q-factor of speaker+cabinet ($M_{AT} \approx M_{AS}$),

$$Q_{TC} = \frac{1}{R_{AT}}\sqrt{\frac{M_{AS}}{C_{AT}}}, \qquad R_{AT} = \frac{(BL)^2}{S_D^2 R_E} + R_{AD} + R_{Af} + R_{Ab} + R_{AB} \tag{47}$$

- Lets look at the Q-factor ratio,

$$\frac{Q_{TC}}{Q_{TS}} = \frac{\frac{1}{R_{AT}}\sqrt{\frac{M_{AS}}{C_{AT}}}}{\frac{1}{R_{AS}}\sqrt{\frac{M_{AS}}{C_{AS}}}} = \frac{R_{AS}}{R_{AT}}\sqrt{1 + \frac{C_{AS}}{C_{AB}}} \tag{48}$$

Cabinet damping: find the volume

- Simplify by defining electrical, mechanical and box Q-factors (using M_{AS}, C_{AS}),

$$Q_{ES} = \frac{S_D^2 R_E}{(BL)^2}\sqrt{\frac{M_{AS}}{C_{AS}}}, \quad Q_{MS} = \frac{1}{R_{AD} + R_{Af} + R_{Ab}}\sqrt{\frac{M_{AS}}{C_{AS}}}, \quad Q_{MB} = \frac{1}{R_{AB}}\sqrt{\frac{M_{AS}}{C_{AS}}} \tag{49}$$

- Now in terms of Q-factors and volumes

$$\frac{Q_{TC}}{Q_{TS}} = \frac{\frac{1}{Q_{ES}} + \frac{1}{Q_{MS}}}{\frac{1}{Q_{ES}} + \frac{1}{Q_{MS}} + \frac{1}{Q_{MB}}}\sqrt{1 + \frac{V_{AS}}{V_{AB}}} \tag{50}$$

- Now, recalling that $V_{AB} = V_A + \gamma V_M$, **solve for** V_A, the free space volume!

Cabinet damping: find the volume

- Free space volume given by,

$$V_A = V_{AB} - \gamma V_M = \frac{V_{AS}}{Q_{TC}^2 \left(\frac{1}{Q_{TS}} + \frac{1}{Q_{MB}} \right)^2 - 1} - \gamma V_M \quad (51)$$

- V_{AS} is the equivalent volume of the driver suspension (TS param), V_M is the volume of absorbent material and V_A is the remaining free space.

- **Problem:** V_A (or C_{ABC}) is required to calculate R_{AB} (for Q_{MB})...
- **Solution:** A first approximation obtained by letting $Q_{MB} \to \infty$

$$V_A = \frac{V_{AS}}{\left(\frac{Q_{TC}}{Q_{TS}} \right)^2 - 1} - \gamma V_M \quad (52)$$

- V_A is then used to obtain R_{AB} and then Q_{MB}. After, we recalculate V_A using the top equation - this is the required free space volume. Then, $V_B = V_A + V_M$.

Lossless vs. lossy

- For an **infinite baffle** we have M_{AS}, R_{AS}, ω_s, and

$$Q_{TS} = \frac{\omega_s M_{AS}}{R_{AS}} \tag{53}$$

- For a **lossless cabinet** we have $M_{AT} \approx M_{AS}$, $R_{AT} \approx R_{AS}$, ω_c, and

$$Q_{TC} = \frac{\omega_c M_{AS}}{R_{AS}} \quad \rightarrow \quad \frac{Q_{TC}}{\omega_c} \approx \frac{Q_{TS}}{\omega_s} \tag{54}$$

- For a **lossy cabinet** we have $M_{AT} \approx M_{AS}$, $R_{AT} \approx R_{AS} + R_{AB}$, ω_c, and

$$Q_{TC} = \frac{\omega_c M_{AS}}{R_{AS} + R_{AB}} \quad \rightarrow \quad \frac{Q_{TC}}{\omega_c} \approx \frac{1}{1 + \frac{R_{AB}}{R_{AS}}} \frac{Q_{TS}}{\omega_s} \tag{55}$$

Lossy design process

1. Define ratio of free space volume V_A to the material V_M e.g. $V_M = V_A/3$
2. Get an initial estimate for the free space volume V_A (assuming $Q_{MB} = \infty$)

$$V_A = \frac{V_{AS}}{\left(\frac{Q_{TC}}{Q_{TS}}\right)^2 - 1} - \frac{\gamma V_A}{3} \rightarrow V_A = \frac{V_{AS}}{\left(1 + \frac{\gamma}{3}\right)\left(\left(\frac{Q_{TC}}{Q_{TS}}\right)^2 - 1\right)} \tag{56}$$

3. Use V_A (or C_{ABC}) to estimate R_{AM} and then R_{AB} and Q_{MB}

$$R_{AM} = \frac{dR_f}{3S_M} \qquad R_{AB} = \frac{R_{AM}}{\left(1 + \frac{C_{ABC}}{C_{ABR}}\right)^2 + \omega^2 R_{AM}^2 C_{ABC}^2} \qquad Q_{MB} = \frac{1}{R_{AB}}\sqrt{\frac{M_{AT}}{C_{AT}}} \tag{57}$$

Lossy design process

3 Use V_A (or C_{ABC}) to estimate R_{AM} and then R_{AB} and Q_{MB}

$$R_{AM} = \frac{dR_f}{3S_M} \qquad R_{AB} = \frac{R_{AM}}{\left(1 + \frac{C_{ABC}}{C_{ABR}}\right)^2 + \omega^2 R_{AM}^2 C_{ABC}^2} \qquad Q_{MB} = \frac{1}{R_{AB}}\sqrt{\frac{M_{AT}}{C_{AT}}} \tag{58}$$

4 Update the volume estimate V_A no longer assuming $Q_{MB} = \infty$

$$V_A = \frac{V_{AS}}{\left(1 + \frac{\gamma}{3}\right)\left(Q_{TC}^2\left(\frac{1}{Q_{TS}} + \frac{1}{Q_{MB}}\right)^2 - 1\right)} \tag{59}$$

5 Calculate resonant frequency using apparent box compliance C_{AB} (or V_{AB})

$$\omega_c = \omega_s\sqrt{1 + \frac{C_{AS}}{C_{AB}}} = \omega_s\sqrt{1 + \frac{V_{AS}}{V_{AB}}} \tag{60}$$

Next week...

- Transmission line cabinet
- Vented cabinets

- Reading:
  - Infinite baffle vs. sealed cabinet. Sec 8.2.1.2
  - Transmission line. Lecture notes Sec. 8.2
  - Vented cabinet. Lecture notes Sec. 8.3