Week 10: The vented cabinet loudspeaker (part 1)

Microphone and Loudspeaker Design - Level 5

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Weekly fact about... your home town!

What's the best fact about your home town?

What are we covering today?

1. Transmission line loudspeaker
2. Vented cabinet design
3. Vented cabinet equivalent circuit
4. Mechanical motion and electrical impedance
5. Tutorial questions

Transmission line loudspeaker

Transmission line loudspeaker: OG (mark 2)

- The sealed cabinet is loaded by a compliant volume of air. Causes a decrease in total compliance and increase of resonant frequency/cut-off.
- How else can we prevent rear radiation interfering?
  - Load driver with an infinite duct/pipe?
- Idea behind the *transmission line* loudspeaker.
- How does an 'infinite duct' effect the driver response?
- **We need to find its acoustic impedance**

$$Z_{Ab} = ?? \tag{1}$$

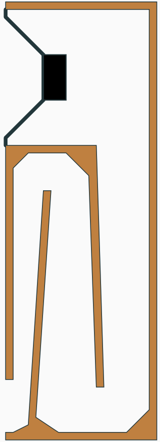

Figure 1: Transmission line loudspeaker.

Infinite pipe: acoustic impedance

- In pipes sound is assumed to be a plane wave:

$$P = P_0 e^{j(\omega t \pm kx)} \tag{2}$$

- From PoA (next semester with Olga) we know that the particle velocity and pressure are related by Euler's eq:

$$\frac{dP}{dx} = -\rho_0 \frac{du}{dt} \tag{3}$$

- This is basically Newton's 2nd Law for a wave $F = ma$

Infinite pipe: acoustic impedance

- Assume infinite pipe length with a travelling wave in one direction:

$$P_+ = P_0 e^{j(\omega t - kx)} \tag{4}$$

- From Euler's eq:

$$\frac{dP}{dx} = -\rho_0 \frac{du}{dt} \quad \rightarrow \quad u = -\frac{1}{\rho_0} \int \frac{dP}{dx} dt \tag{5}$$

- Substitute travelling wave

$$u = -\frac{1}{\rho_0} \int \frac{d}{dx} P_0 e^{j(\omega t - kx)} dt = \frac{jk}{j\omega\rho_0} P_0 e^{j(\omega t - kx)} = \frac{1}{\rho_0 c} P_+ \tag{6}$$

Infinite pipe: acoustic impedance

- We have the pressure velocity relation,

$$u = \frac{1}{\rho_0 c} P_+ \tag{7}$$

- The *specific* acoustic impedance is then

$$z = \frac{P_+}{u} = \rho_0 c \tag{8}$$

- The acoustic impedance (i.e. pressure over *volume* velocity)

$$U = uS \quad \rightarrow \quad Z_A = \frac{P_+}{U} = \frac{\rho_0 c}{S} \tag{9}$$

- **This impedance is purely resistive!**

Transmission line loudspeaker: acoustic loading

- The impedance of an infinite pipe is purely real - it has no reactive part.
- Loading a loudspeaker by an infinite pipe (i.e. a transmission line) **will not change** the resonant freq. of the driver.
- Acoustic front load (same as before)

$$Z_{Af} = R_{Af} + j\omega M_{Af} \tag{10}$$

- Rear acoustic load

$$Z_{Ab} = R_{Ab} = \frac{\rho_0 c}{S} \tag{11}$$

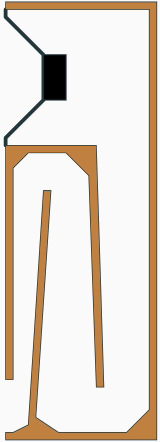

Figure 2: Transmission line loudspeaker.

Transmission line loudspeaker: equivalent circuit

- No added compliance - no increase in resonant freq. $f_s = f_c$ - improved low freq. response compared to a sealed cabinet.
- Absorbent material provides more or less anechoic back-load.
- Length of duct typically $\approx \lambda/2$ - constructive interference between port and driver

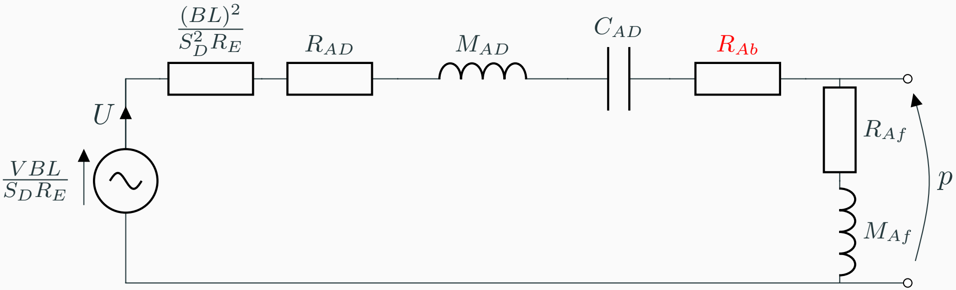

Figure 3: Transmission line equivalent circuit.

Vented cabinet design

Vented cabinet loudspeaker: the GOAT

- **Problem:** sealed/transmission line cabinet low frequency cut-off limited by f_s
- **Solution:** the vented cabinet
- Why?
  - Extend the low frequency performance
  - Control cone movement
  - Utilise radiation from the rear
- How?
  - Take a sealed cabinet
  - Add hole with port (circular or rectangular)
  - Cross fingers and hope it works?

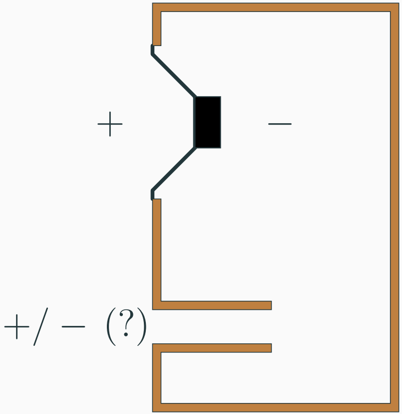

Figure 4: Vented cabinet loudspeaker.

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

Vented cabinet loudspeaker: parameters

- Driver/diaphragm:

  M_{AD}, C_{AD}, R_{AD} - mechanical mass, compliance and damping
  $M_{Af,b}$, $R_{Af,b}$ - acoustic loading (piston)
  U_D - volume velocity

- Cabinet:

  C_{AB}, R_{AB} - compliance and damping
  U_B - volume velocity

- Vent:

  M'_{AV}, R'_{AV} - mass and damping
  $M_{AV\,f,b}$, $R_{AV\,f,b}$ - acoustic loading
  U_V - volume velocity

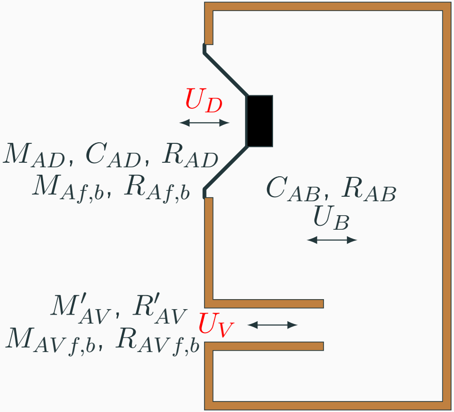

Figure 5: Vented cabinet loudspeaker.

Vented cabinet loudspeaker: a two DoF system

- The degree of freedoms (DoF) of a mechanical (or acoustical) system is the number of independent parameters that define its configuration.
- **Number of DoFs = number of resonant frequencies**
- Sealed cabinet is a 1 DoF vibrating system:
  - Velocity of driver U_D
- Vented loudspeaker is a 2 DoF vibrating system:
  - Velocity of driver U_D
  - Velocity of vent mass U_V
  - (*We also define the box velocity* $U_B = U_D - U_V$)
- Vent mass adds an extra resonant frequency to the loudspeaker system...
- To determine the behaviour of a vented loudspeaker we need to analyse the 2 DoF system. We will use an equivalent circuit approach.
  - Really great MIT lecture on 2 DoF systems!

Vented cabinet loudspeaker: parameters

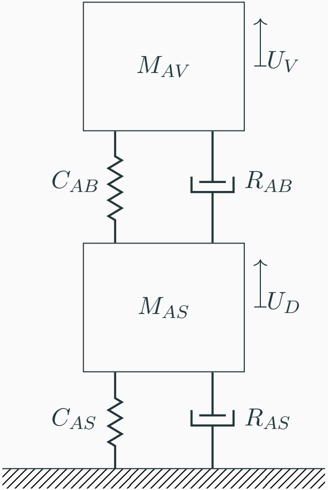

Figure 6: Equivalent mechanical model.

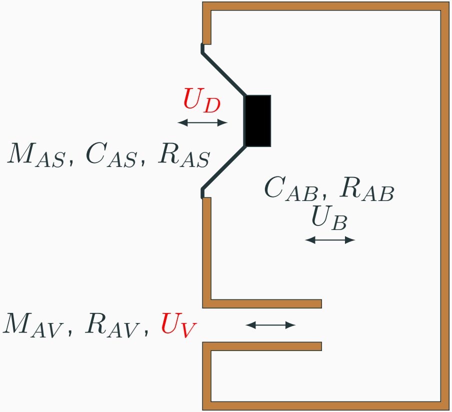

Figure 7: Vented cabinet loudspeaker.

Vented cabinet loudspeaker: box volume velocity

- Here is a link to an experimental example of a 2 DoF system
  - 2:40 – in phase motion (out of phase driver/vent)
  - 4:20 – minimum response of first mass (maximum vent velocity)
  - 8:20 – out of phase motion (in phase driver/vent)
- Depending on frequency of excitation the masses have different relative motions
- At resonance these motions are the natural modes of the system

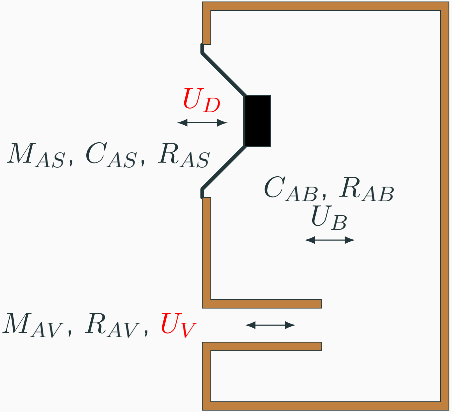

Figure 7: Vented cabinet loudspeaker.

Vented cabinet equivalent circuit

Sealed cabinet loudspeaker: equivalent circuit

- **Sealed cabinet** - single DoF - only one velocity/current
- Note that there is only one loop.
- All elements share the same current (or volume velocity).

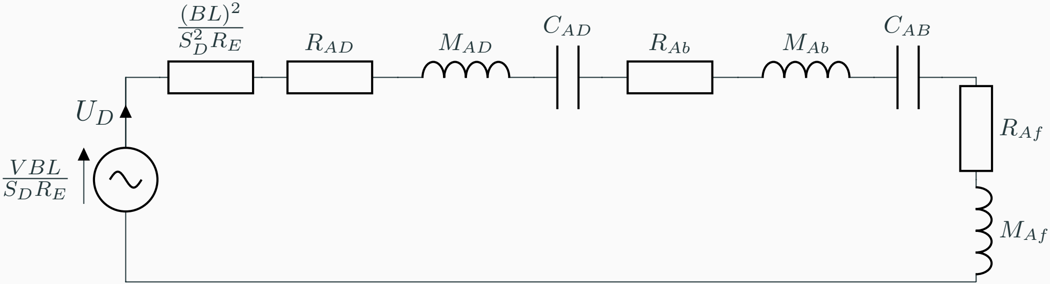

Figure 8: Complete equivalent circuit for lossless sealed cabinet.

Vented cabinet loudspeaker: equivalent circuit

- **Vented cabinet** - two DoFs - three velocities/currents (including box U_B)
- There are now two loops!
- The supplied current U_D is separated into U_V and $U_B = U_D - U_V$

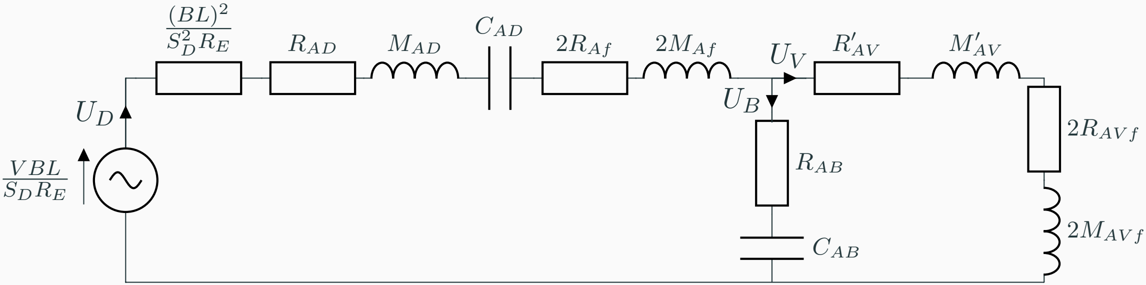

Figure 9: Complete equivalent circuit for vented cabinet.

Vented cabinet loudspeaker: equivalent circuit

- To make life easier we can group all acoustic loading terms within the driver and vent mass/damping
- To design a vented loudspeaker we will need to analyse this circuit (but not today..!)

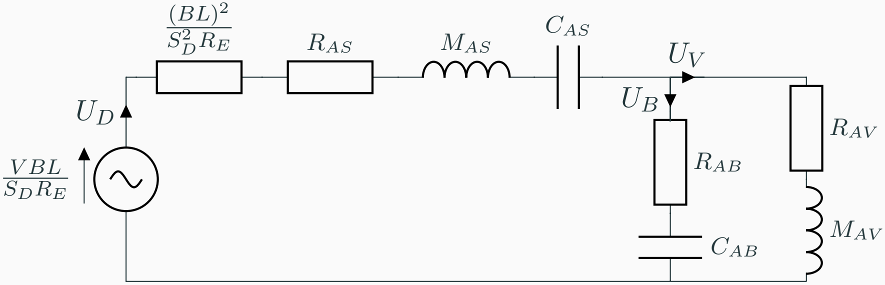

Figure 10: Simplified complete equivalent circuit for vented cabinet.

Mechanical motion and electrical impedance

Vented cabinet loudspeaker: diaphragm and vent velocity

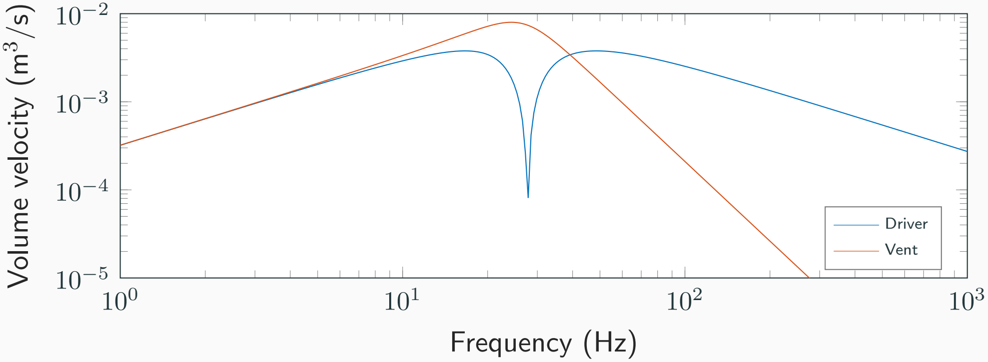

Figure 11: Volume velocity of diaphragm and vent of vented loudspeaker.

- As expected we get two resonant frequencies in the diaphragm velocity
- How does this response translate the electrical impedance and radiated pressure?

Vented cabinet loudspeaker: electrical impedance

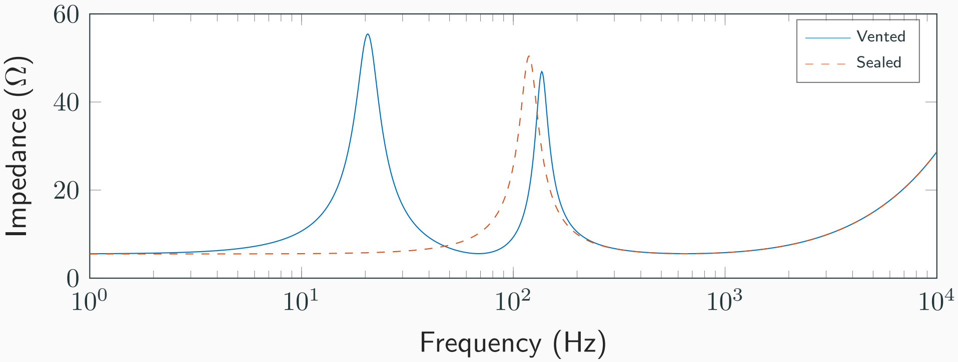

Figure 12: Electrical impedance of vented and sealed loudspeaker.

- Large driver velocity → large back EMF → increased electrical impedance
- Two peaks in electrical impedance back system has two resonant frequencies

Electrical impedance: lower resonance

- At lowest resonance f_L cavity acts 'rigidly' - masses move together in phase
- $f_L < f_s$ due to added vent mass.
- Driver and vent are 180° **out of phase**
  - As the driver moves outwards, the mass of the vent is sucked inwards
  - As the driver moves inwards, the mass of the vent is pushed outwards
  - Destructive interference leads to **poor radiation** around f_L
- Large diaphragm velocity - increased electrical impedance due to back EMF

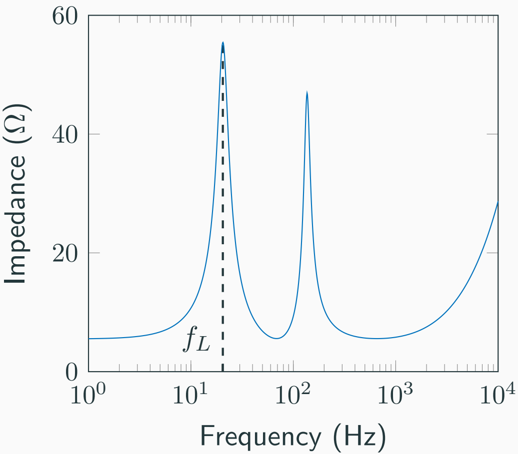

Figure 13: Vented electrical impedance.

Electrical impedance: lower resonance

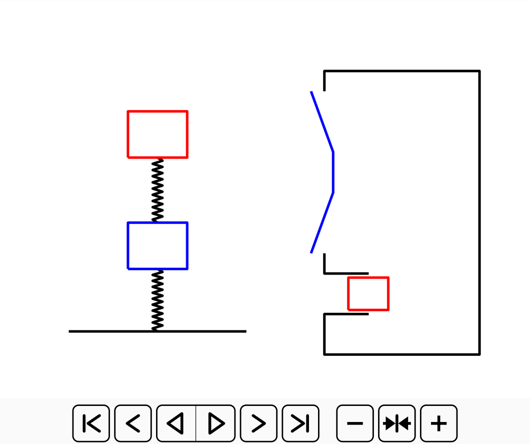

Figure 14: Behaviour at lower resonance

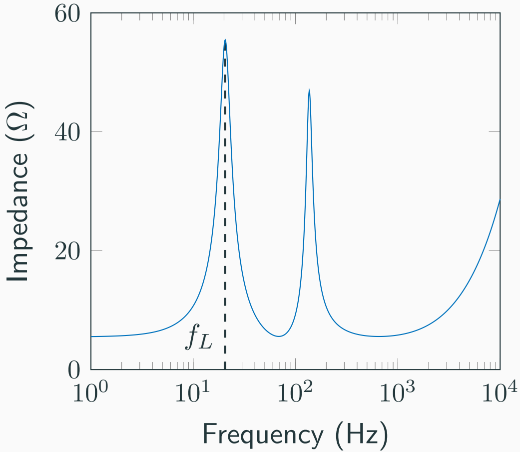

Figure 13: Vented electrical impedance.

Electrical impedance: upper resonance

- At upper resonance f_H the cavity acts like a spring - masses bounce on the cabinet compliance
- Driver and vent are 180° **out of phase**
  - Mass-spring-mass move in opposite directions
  - Driver/vent move in **same direction**
  - Constructive interference leads to **efficient radiation** around f_H
- Large diaphragm velocity - increased electrical impedance due to back EMF

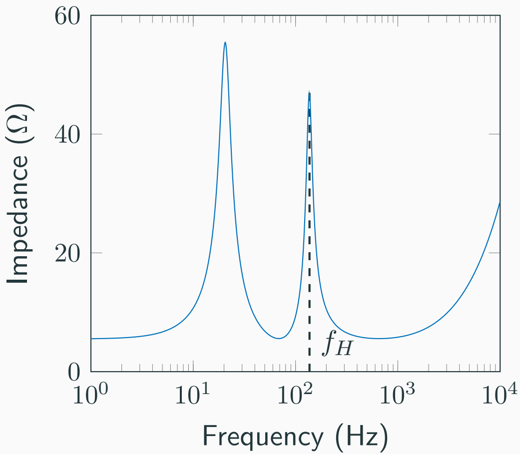

Figure 15: Vented electrical impedance.

Electrical impedance: upper resonance

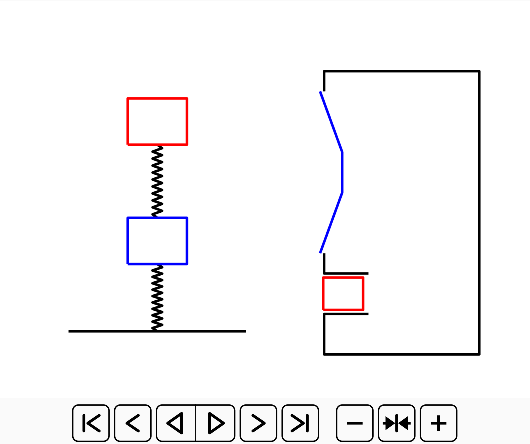

Figure 16: Behaviour at upper resonance

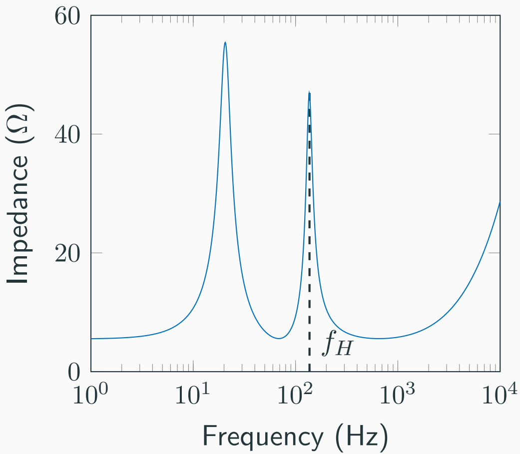

Figure 15: Vented electrical impedance.

Electrical impedance: minimum/Helmholtz frequency

- The minimum frequency occurs at the **Helmholtz frequency** of the cabinet
- $U_D = 0 \rightarrow f_M$ is independent of driver
- The driver velocity is fixed - vent mass is bouncing on a cavity volume

$$f_M = \frac{1}{2\pi}\sqrt{\frac{1}{M_{AV}C_{AB}}} \qquad (12)$$

- Tiny diaphragm velocity - minimal back EMF - DC resistance $Z_E \approx R_E$

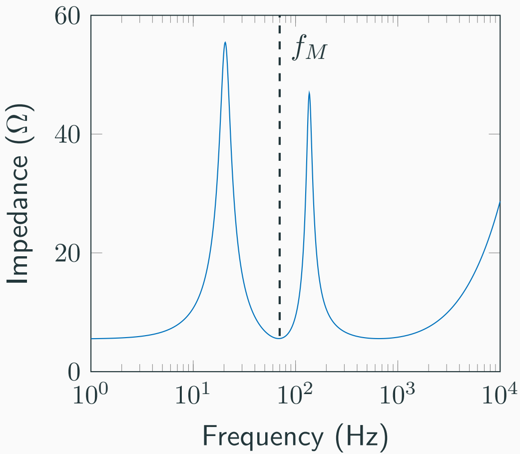

Figure 17: Vented electrical impedance.

Electrical impedance: Helmholtz resonance

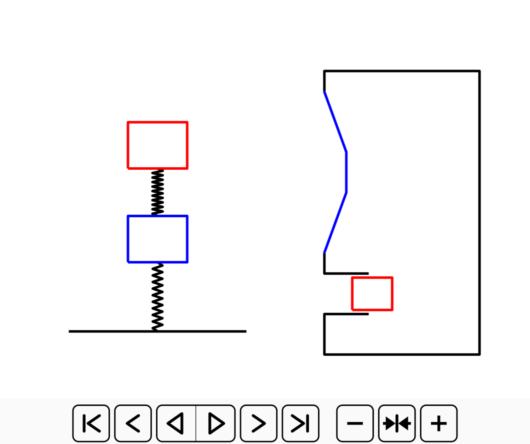

Figure 18: Behaviour at Helmholtz resonance

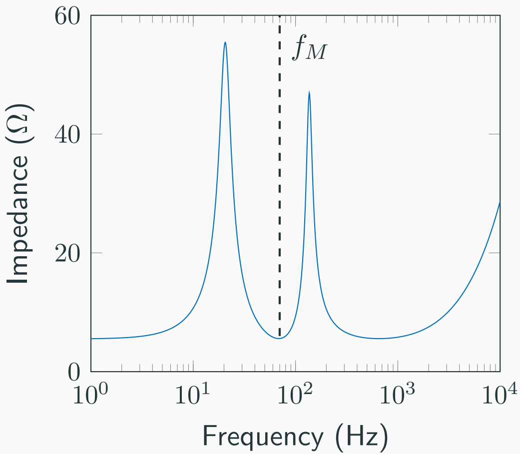

Figure 17: Vented electrical impedance.

Vented cabinet: pressure contributions

- At Helmholtz resonance f_M:
  - Driver output minimum
  - Vent output maximum (most of the output)
- At lower resonance f_L:
  - Driver/vent rigidly coupled and out of phase
  - Destructive interference causes sharp roll off
- At upper resonance f_H:
  - Driver/vent bounce on cabinet compliance
  - In-phase and combine constructively
- Above upper resonance:
  - Vent mass inertia causes roll off in output
  - Driver only sees the cabinet and behaves like sealed cabinet

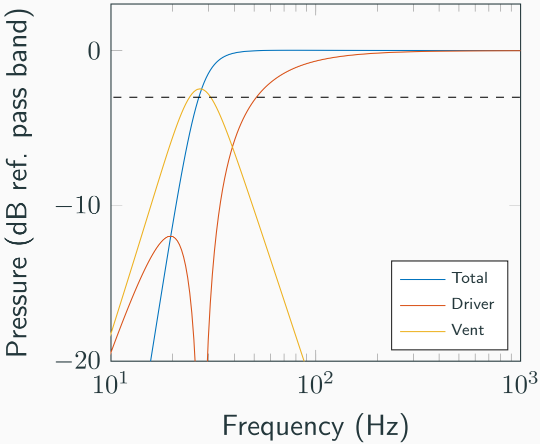

Figure 19: Vented pressure contributions.

Sealed vs. vented cabinet response

- Sealed cabinet:
  - Poor low freq. response (limited by f_s of driver)
  - Roll of is 12 dB/oct (this is a 2nd order effect)
- Vented cabinet:
  - Extended low frequency response due to vent contribution
  - Roll of is 24 dB/oct (this is a 4th order effect due to the 12 dB/oct for both driver and vent)
- Check out this video! Vented sub in action.

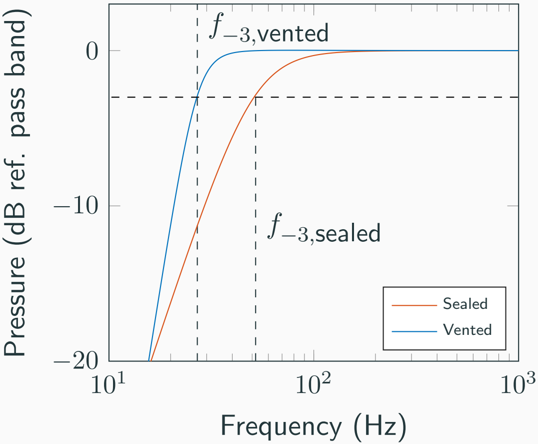

Figure 20: Sealed vs. vented cabinet response for the same driver.

Tutorial questions

Tutorial questions

Click to open tutorial questions!

Next week...

- Circuit analysis and design procedure for vented cabinets.
- Reading:
  - Vented cabinet. Lecture notes Sec. 8.3