Week 12: Performance parameters and magnet/voice coil design

Microphone and Loudspeaker Design - Level 5

Joshua Meggitt

Acoustics Research Centre, University of Salford

What are we covering today?

1. Frequency response
2. Directivity
3. Sensitivity
4. Rated power
5. Magnet/voice coil assemblies

Performance parameters

- **Frequency response** – describes the radiated sound pressure level as a function of frequency (we have already covered this with our functions $E(j\omega)$ and $F(j\omega)$)
- **Directivity** – describes the radiated sound pressure level as a function of angle (we have partly covered this with our rigid piston model)
- **Sensitivity** – describes the radiated sound pressure level in dB at a fixed distance of 1m for 1 watt of input power.
- **Efficiency** – is the percentage of electrical input power that is converted to acoustic power.
- **Rated power** – how much power the speaker is designed to safely receive from an amplifier before unacceptable distortion or failure.

Frequency response

Performance parameters: frequency response

- **Sealed cabinet** – 12 dB/oct roll-off

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

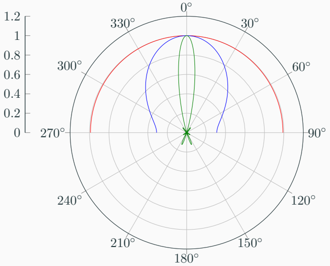
- **Vented cabinet** – 24 dB/oct roll-off

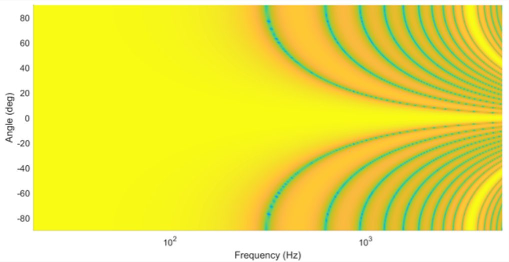
$$F(j\omega) = \frac{1}{\left(1 + \frac{\omega_s}{j\omega}\frac{1}{Q_{TS}} + \left(\frac{\omega_s}{j\omega}\right)^2\right)\left(\left(\frac{\omega_b}{j\omega}\right)^2 + 1\right) + \alpha\left(\frac{\omega_s}{j\omega}\right)^2} \tag{2}$$

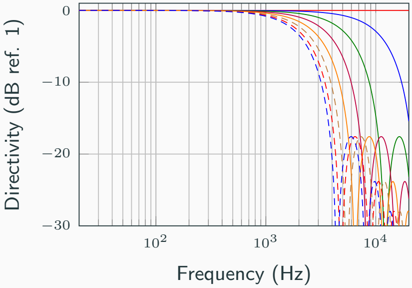
Directivity

Performance parameters: directivity

- Direction sound is being radiated most
- Directivity commonly shown on a polar plot or as multiple frequency response plots
- Can use surface plots to show directivity and frequency response.







Performance parameters: directivity

- We can predict the directivity using our rigid piston model:

$$p(r,\theta,t) = \frac{j\rho_0 ckU}{4\pi r} e^{j(\omega t - kr)} \overbrace{\left[\frac{2J_1(ka\sin\theta)}{ka\sin\theta}\right]}^{\text{Directivity factor}} \quad (3)$$

- Gives us omni-directional response at low frequency, and beam-like directivity at high frequencies

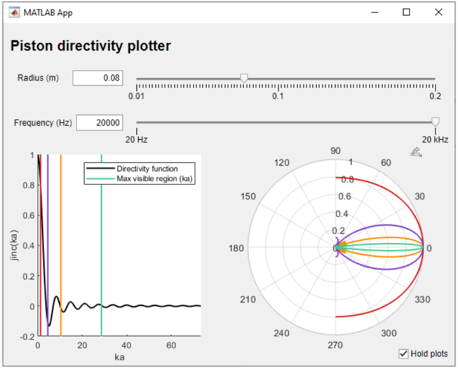


Figure 1: MATLAB applet. Available to download.

Performance parameters: directivity

- There are two common quantities for specifying directivity.
- Directivity Factor $Q(f)$ – the ratio of the intensity of the speaker I_s at a stated distance r to the intensity that would be produced by a point source I_p with the same total acoustic power.

$$Q(f) = \frac{I_s(f)}{I_p(f)} \tag{4}$$

- Directivity Index $DI(f)$ – 10 times the logarithm to the base 10 of the directivity factor.

$$DI(f) = 10 \log_{10}(Q) \tag{5}$$

Performance parameters: directivity

- Generally, loudspeaker drivers have narrower directivity at high frequencies
- We often want a uniform directivity across frequency range
    - This is why we use increasingly small drivers for higher frequencies
- We can use multiple drivers and their interference to carefully control directivity – beam forming.
    - More on this next semester!

Sensitivity

Performance parameters: sensitivity

- **Definition:** average SPL for 1 Watt at 1 meter on axis

$$\text{Sensitivity} = 20\log_{10}\left(\frac{p}{p_{ref}}\right)_{\text{(1m @ 1W)}} \tag{6}$$

- First need to find out what voltage provides 1 Watt of electrical power

$$W_E = V \times I = \frac{V^2}{Z_E} \rightarrow \frac{V^2}{R_E} = 1 \tag{7}$$

$$V = \sqrt{R_E} \tag{8}$$

- Then we can use our equivalent circuit model to predict the radiated SPL.

Performance parameters: sensitivity

- For sealed and vented loudspeakers we can predict the on axis response,

$$p_{(\text{1m @ 1W})} = \frac{\rho_0 BL}{2\pi c S_D R_E M_{AT}} \sqrt{R_E} \times E(j\omega) \text{ or } F(j\omega) \tag{9}$$

- Sensitivity is typically specified for passband regime $(E(j\omega), F(j\omega) = 1)$

$$\text{SPL} = 20 \log_{10} \left(\frac{p}{p_{ref}} \right)_{(\text{1m @ 1W})} \tag{10}$$

- Typical sensitivity values:
  - Typically around 88dB 1W @ 1m
  - $<$80dB 1W @ 1m flat panel speakers
  - $>$95dB 1W @ 1m professional monitors

Rated power

Performance parameters: rated power

- If loudspeakers are driven by too high an electric power 2 things can occur: unacceptable distortion and driver failure.
  - Distortion: when driven by a single pure tone, non-linearities due to high excitation levels introduce extra frequencies which colour the sound.
  - Failure: when driven too hard loudspeakers can face permanent damage or even failure.
- A power handling is specified as the amount of input power a driver can take before unacceptable distortion or failure occurs.

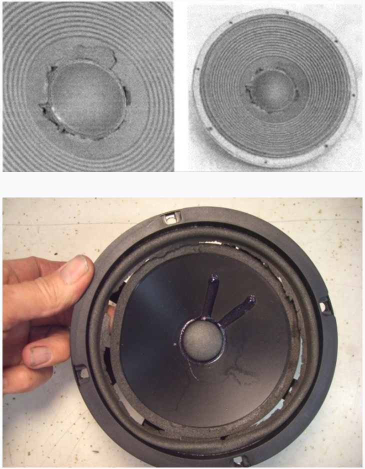


Figure 2: Cone damage example.

Performance parameters: rated power

- Combined with the sensitivity we can predict the maximum operating level.
- E.g. a 4Ω speaker rated at 35 W with a sensitivity of 85 dB (1m @ 1W):

$$35 = \frac{V^2}{R_e} \rightarrow V = \sqrt{35}\sqrt{4} \tag{11}$$

$$\text{Max SPL} = 20\log_{10}\left(\frac{p_{(\text{1m @ 1W})} \times \sqrt{35}}{p_{ref}}\right) \tag{12}$$

$$\text{Max SPL} = 20\log_{10}\left(\frac{p_{(\text{1m @ 1W})}}{p_{ref}}\right) + 20\log_{10}\left(\sqrt{35}\right) \tag{13}$$

$$\text{Max SPL} = 85 + 10\log_{10}(35) = 100.4 \text{ dB} \tag{14}$$

Performance parameters: loudspeaker failure

- **Thermal** failure:
  - Thermal is the most common of failure modes, and often unfairly blamed on the loudspeaker driver itself.
  - Failures occur from too much current when an amplifier's continuous output reaches beyond the heat dissipation capabilities of the loudspeaker's voice coil.
  - Loudspeakers are very inefficient devices, on average 0.5-5% of power supplied is converted to sound; the rest is converted to heat.
  - If a loudspeaker is unable to dissipate that heat quickly enough the speaker will fail.
- **Mechanical** failure:
  - Mechanical failure occurs when the transducer cone or diaphragm, voice coil or suspension systems are forced to physically move beyond their limits.
  - Typically, this is the result of amplifier peak voltage being too high. The result is over-excursion that can cause the coil to move out of the voice coil gap completely, or hit the back plate – known as 'bottoming-out'.
  - Misconfigured cabinet designs can also cause excursion problems.

Performance parameters: nominal power rating (AES2-2012)

- How much power a speaker can handle gives no indication of its performance at full power or how loud it will be. It tells you that's how much power it can survive.
- Nominal power ratings according to AES2-2012 standards:
  - Transducer mounting: low frequency drivers are tested in free air orientated in the horizontal axis.
  - Transducers under test are driven with a band of pink noise extending one decade upward from the manufacturer's stated lowest usable frequency.
  - Calculation ($P = V^2/Z_{norm}$): power shall be determined as the square of applied RMS voltage, as measured with a 'true RMS' voltmeter, divided by Z_{norm}.
  - The rated power of the device shall be that power the device can withstand for 2 hours without permanent change in acoustical, mechanical, or electrical characteristics greater than 10%.

- Crest factor between 3 and 4 - peak amplitude of the waveform divided by RMS value:

$$\text{CF}_{\text{dB}} = 20\log_{10}\left(\frac{|V_{peak}|}{|V_{RMS}|}\right) \tag{15}$$

- Pink noise over one octave starting from lowest rated frequency

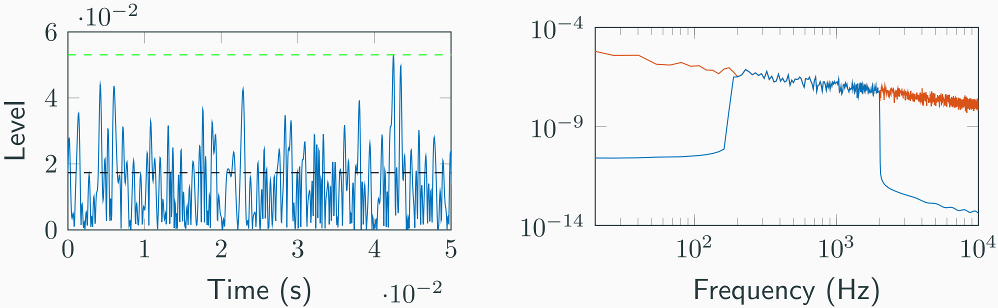


Figure 3: Example AES2-2012 test signal (200-2000 Hz, CF=3.4=10.9 dB).

Performance parameters: other types of power

- **RMS (average) power** (similar to nominal, but not the same! Test not as strict.)
  - Root Mean Square is used to compare the AC power to the equivalent DC power required to provide the same heating capacity into the load.
- **Peak power** (usually we want to ignore this!)
  - This is the amount of power the speaker can take for very brief periods at a time.
  - Peak power is not representative: typical content last no more than a few milliseconds.
- **PROGRAMME** (not really used any more...)
  - Although having no specific meaning, it's generally accepted that it is the amount of power that a speaker can handle during typical music or 'typical program' where frequency content and power constantly vary.
  - Program power is typically given as twice that of the nominal power rating.

Magnet/voice coil assemblies

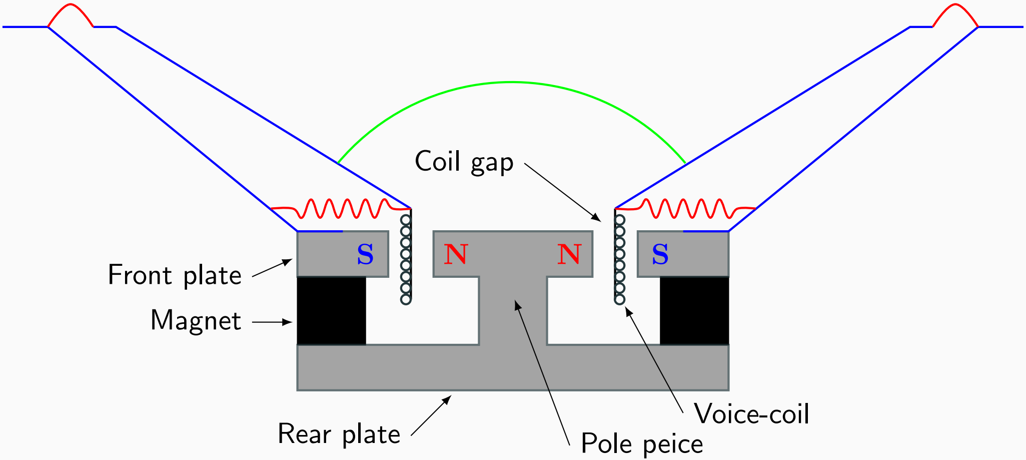


Figure 4: Magnet assembly

Basic electromagnetism

- Magnetic fields are generated by moving charges:
  - Electromagnetic using a current moving through a coil of wire
  - Permanent magnets rely of atomic motion (orbit and spin) of electrons
- When in motion, a charge creates a magnet field parametrised by field strength H (A/m)
- The field is often described by another parameter, the flux density B (T)
  - Describes how closely the field lines are packed together
- B and H are related by the permeability of the medium

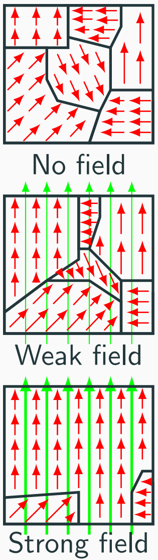
$$B = f(H, \mu_r) \tag{16}$$

Basic electromagnetism

- In a vacuum H and B are related by: $B = H\mu_0$
  - μ_0 is the permeability of free space
  - As the field strength is increased, the flux density increases proportionally
- In a material the relation between H and B can be more complex
  - For ‘non-magnetic’ materials $B = \mu_r\mu_0 H$ where μ_r is the relative permeability of the material. The material increases flux density.
  - For ‘magnetic’ materials the relationship is more complex and multi-valued and is described by magnetic hysteresis...

Magnetic domains

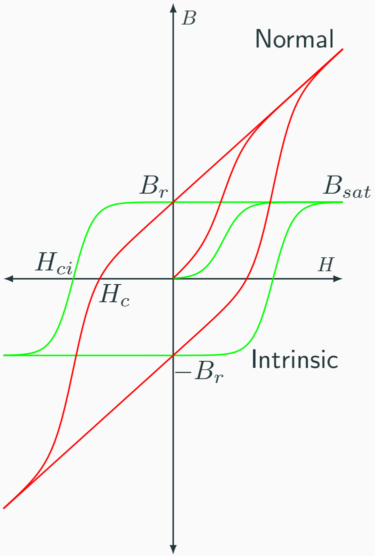
- Atoms have permanent magnetic dipole moments - in a ferromagnetic these dipoles are aligned parallel to one another over extensive regions called ‘domains’.
- In its natural (demagnetised) state these domains are randomly orientated. The net magnetism is then 0!
- When placed in a magnetic field the domains can grow/shrink.
- For small movements the process is reversible by reversing the external field
- For large movements the process cannot be reversed by reversing the applied field. The material is now magnetised.
- The magnetisation/demagnetisation process is described by a hysteresis curve.



- In a magnetic material the magnetic flux density B is equal to:

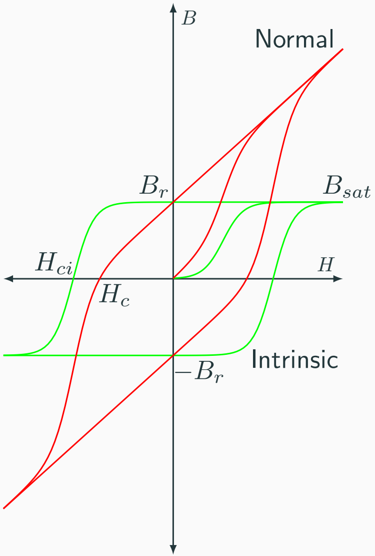
$$B = \mu_0 H + \mu_r \mu_0 M \tag{17}$$

  where $\mu_r \mu_0 M$ is an additional field generated by the material when in the presence of H
- For large field strengths M is a non-linear function of H and is described by the intrinsic curve



Operating points and demagnetisation

- The voice coil gap flux depends on the magnet assembly design (e.g. voice coil gap/area) - it is less than residual flux B_r
- Specifies the 'operating point' of the magnet
- Voice coil current creates small external field H - this moves the operating point up and down the green curve
- If the external field is too great, working point goes over the knee - **causes irreversible demagnetisation**
- Design magnet to keep operating point away from the knee, and avoid too large currents.



Lorentz force - driving the voice coil

- Moving charge in a magnetic field is subject to Lorentz force

$$\vec{F} = q\left(\not{\vec{E}} + \vec{v} \times \vec{B}\right) \tag{18}$$

- Over voice coil of length L charge motion $\vec{v}$ is perpendicular to $\vec{B}$, so

$$|F| = |B|Li \tag{19}$$

- Greater the flux density, the greater the force...

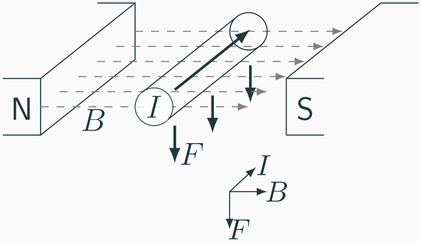


Figure 5: Lorentz force on charge carrying conductor

Magnet structure

- For practical reasons voice coils are cylindrical, so typical magnets are toroidal.
- Two types of toroidal magnet design:
  - External - voice coil sits within the magnet
  - Internal - magnet sits within the voice coil
- Magnetic fields follow path of least reluctance
- **General idea**: use high permeability materials (e.g. steel) to 'direct' magnetic field across voice coil - *pole piece and top plate*

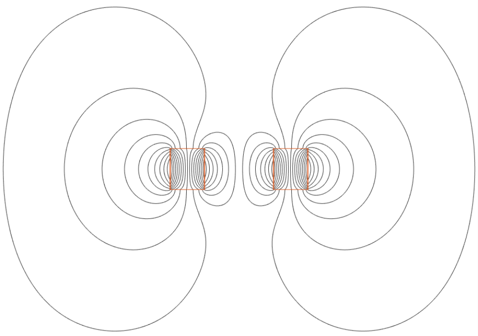


Figure 6: Field lines of stand alone toroidal magnet

Pole piece and top plate - directing the flow

- Pole piece and top plate ‘guide’ and concentrate magnetic field across the voice coil gap, increasing the flux density $\vec{B}$
- Flux of toroidal magnets prefer the outside path – causes flux leakage (want to minimise this) - what about an internal magnet design?

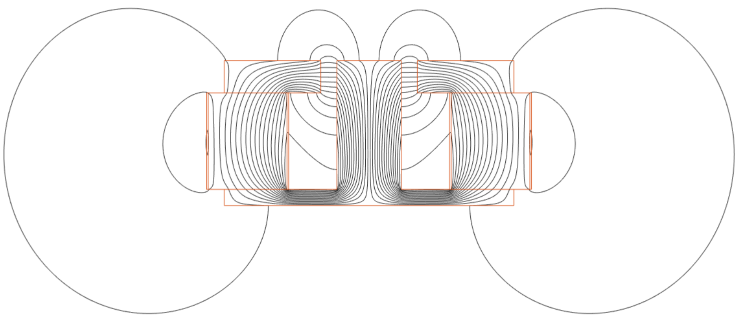


Figure 7: Field lines of external toroidal magnet with top plate and pole piece

Magnet pole-piece - directing the flow

- Keep the voice coil outside magnet – use the natural flux path of the magnet – reduces leakage.

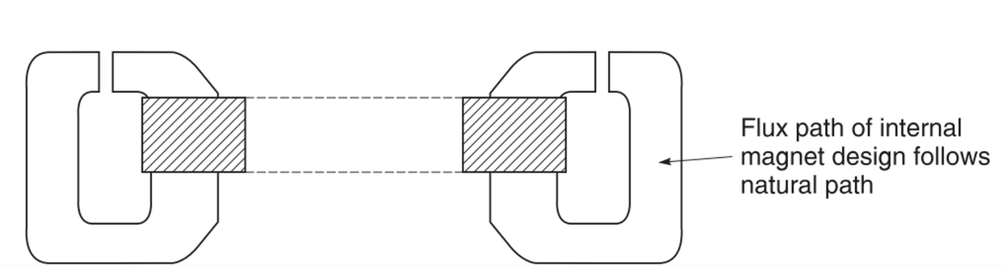


Figure 8: Design of internal toroidal magnet

Coil gap - flux distribution

- We want the voice coil to receive the same forcing irrespective of its displacement.
- Need to have a **uniform flux distribution** across the gap
- If the flux density B depends on displacement, we get non-linear forcing term,

$$F = |B|Li \rightarrow F(x) = |BL(x)|i \qquad (20)$$

- Non-linearity causes audible distortion! **BAD NEWS.**

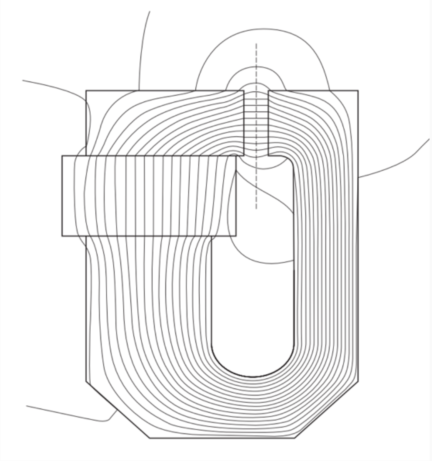


Figure 9: Field lines of through voice coil gap

Coil gap - flux distribution

- We want the flux distribution to have a flat top and be symmetric

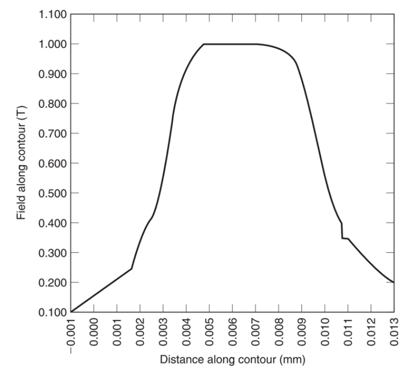


Figure 10: Flux distribution across coil gap

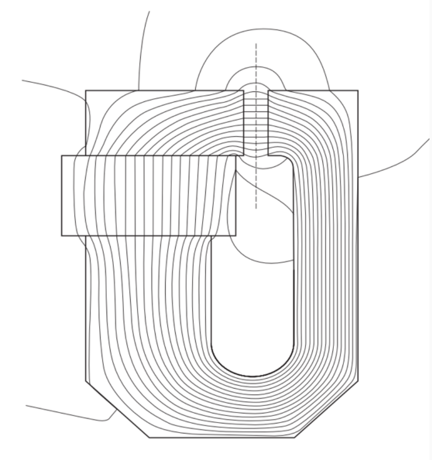


Figure 11: Field lines of through voice coil gap

Voice coil gap - flux density distribution

- We can improve flux distribution by altering the pole piece/top plate geometry - perhaps through numerical optimisation.
- We can also alter the voice coil sizing...

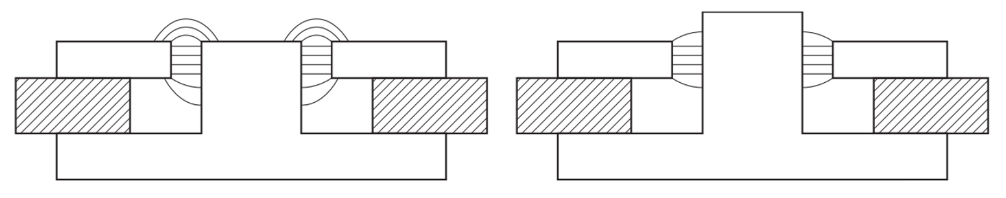


Figure 12: Example of improved pole piece design

Voice coil sizing - over vs. under

- **Underhung coil** - coil is made shorter than the gap so as it is displaced in remains entirely within the uniform flux region.
  - Downside of this design is that the smaller coil generates a smaller force
    Gives hard non-linearity, i.e. it has a quick onset.
- **Overhung coil** - coil is made longer than the gap so main flux will remain within the area of the voice coil.
  - Downside of this design is that it is less efficient
  - Non-linearity is ‘soft’, i.e. has a slow on set.

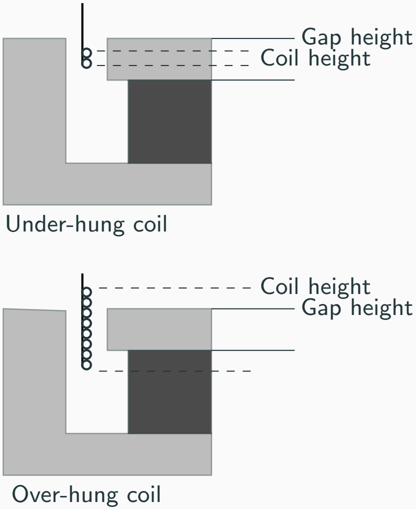


Figure 13: Voice coil sizing

Forcing factor

- The total transduced force depends on the flux distribution and voice coil size.
- Integrate over voice coil height h - at VC position x_0 we could write,

$$F(x) = \int_{x_0-\frac{h}{2}}^{x_0+\frac{h}{2}} |B(x)|Li \, \mathrm{d}x \qquad (21)$$

- The force depends on displacement! This means we have a **NON-LINEARITY**!

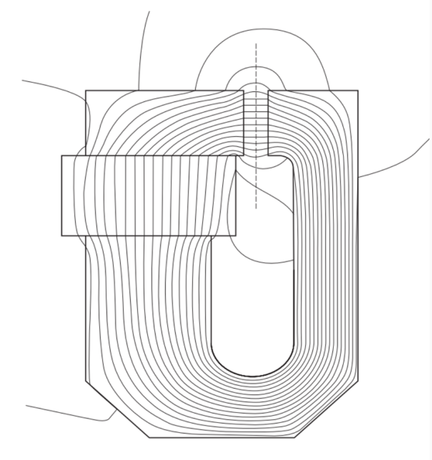


Figure 14: Field lines of through voice coil gap

MATLAB simulation example

- Lets have a look at what this non-linearity does to our loudspeaker response...
  - Spoiler: its not good..!
- MATLAB code simulates the non-linear ordinary differential equation:

$$F(x) = M\ddot{x}(t) + R\dot{x}(t) + Kx(t) \tag{22}$$

- The non-linear forcing factor $F(x)$ is obtained from a Finite Element (FE) magneto-static simulation of a simple magnet assembly.

- *Note: we actually get a similar effect with the suspension stiffness too, it depends on displacement!* $K \rightarrow K(x)$

Next week...

- **Guest lecture and assessment drop in!**
- **Best Christmas jumper will win a pretty awesome prize...**
- **Next semester:**
  - Cross-over design
  - Line arrays
  - Microphone design