

Eddy currents

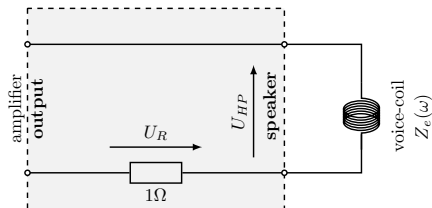
Antonin NOVAK

<https://imdea.ant-novak.com/>

Laboratoire d'Acoustique de l'Université du Maine, Le Mans, France



Experimental setup



$$R_e(\omega) = \Re\{Z_e(\omega)\}$$

apparent resistance

$$L_e(\omega) = \frac{\Im\{Z_e(\omega)\}}{\omega}$$

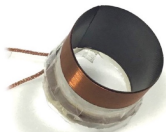
apparent inductance

experiment n.1

voice-coil in air vs. voice-coil inside motor

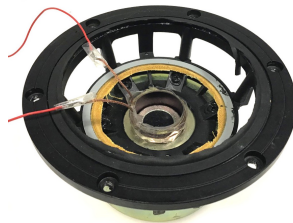
experiment n.1

voice-coil in air

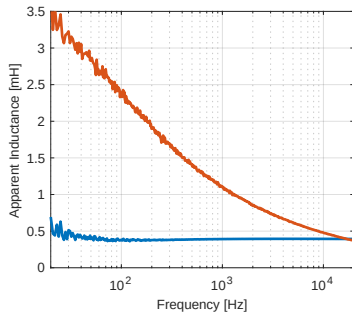
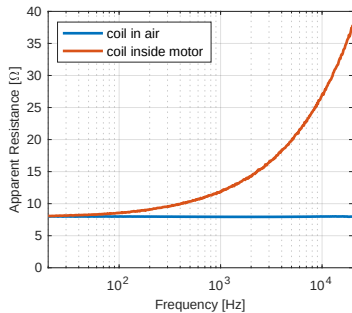


vs.

voice-coil inside motor

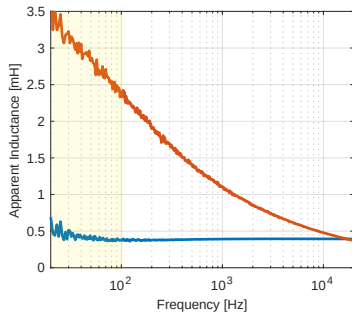
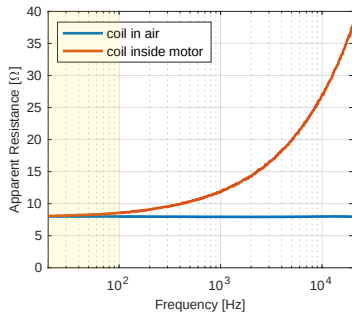


experiment n.1



What is an Inductance L_e ?

low frequencies - inductance effect



Inductance

$$E = \frac{1}{2}Li^2$$

coil inductance



kinetic energy

$$E = \frac{1}{2}mv^2$$

mass of the carousel



kinetic energy



Inductance

$$E = \frac{1}{2} Li^2$$

coil inductance

↓
kinetic energy

$$E = \frac{1}{2} mv^2$$

mass of the carousel

↓
kinetic energy



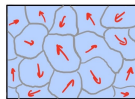
permeability μ

Magnetic domains in iron
(tiny magnets $\approx$ tiny current loops)
line up with the coil field

↓
stronger field

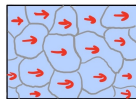
↓
more kinetic energy

initial stage



domains
randomly aligned

external magnetic
field



domains
aligned

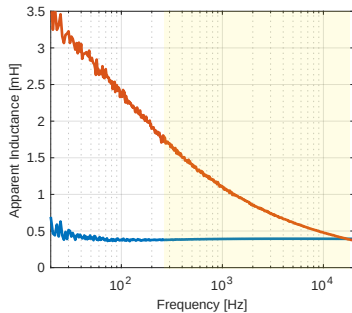
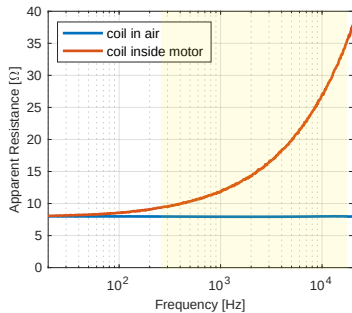
experiment n.1

at low frequencies:

R_e remains the same for air and motor

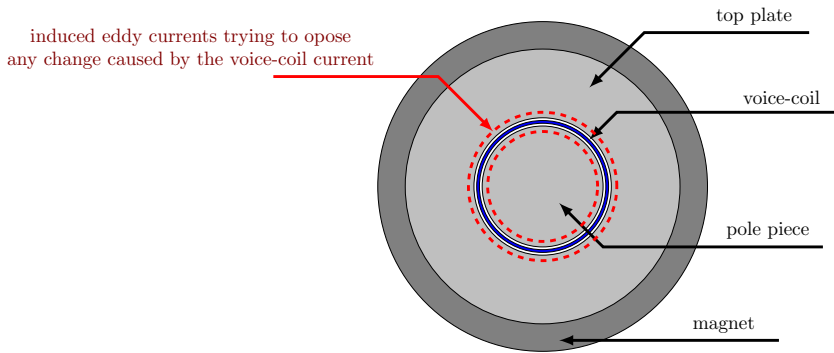
$L_e = \mu \frac{N^2 S}{h}$ is much higher in motor (high permeability μ of iron)

mid/high frequencies - eddy currents



What are eddy currents ?

eddy currents are induced currents that occur on parts that weren't supposed to carry currents.



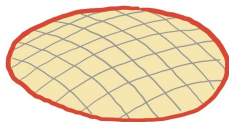
loudspeaker motor: top view

Maxwell–Faraday equation (Faraday's law of induction)

$$\oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$$

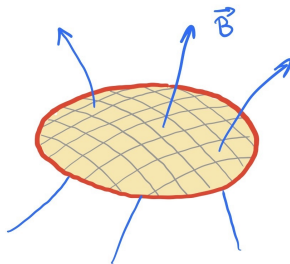
Maxwell–Faraday equation (Faraday's law of induction)

$$\oint_{\partial \Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$$



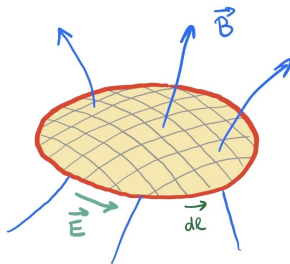
Maxwell–Faraday equation (Faraday's law of induction)

$$\oint_{\partial \Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \vec{\mathbf{B}} \cdot d\mathbf{S}$$



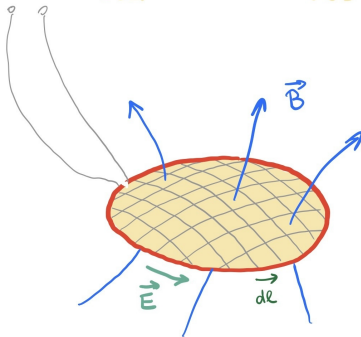
Maxwell–Faraday equation (Faraday's law of induction)

$$\oint_{\partial \Sigma} \vec{E} \cdot d\vec{\ell} = - \frac{d}{dt} \iint_{\Sigma} \vec{B} \cdot d\vec{S}$$



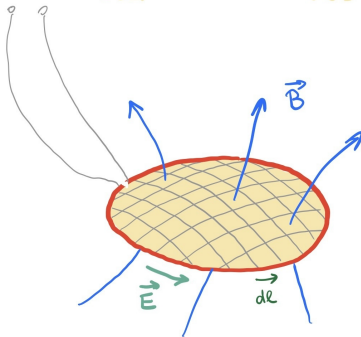
Maxwell–Faraday equation (Faraday's law of induction)

induced voltage $\mathcal{U}_{emf} = \oint_{\partial \Sigma} \vec{E} \cdot d\vec{\ell} = - \frac{d}{dt} \iint_{\Sigma} \vec{B} \cdot d\vec{S}$



Maxwell–Faraday equation (Faraday's law of induction)

induced voltage $\mathcal{U}_{emf} = \oint_{\partial \Sigma} \vec{E} \cdot d\vec{\ell} = -\frac{d}{dt} \iint_{\Sigma} \vec{B} \cdot d\vec{S} = -\frac{d\phi}{dt}$

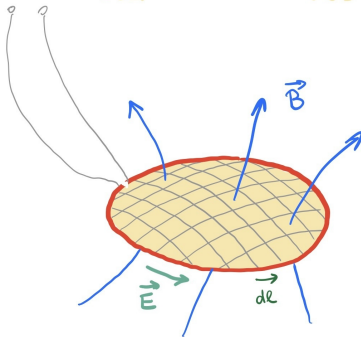


Maxwell–Faraday equation (Faraday's law of induction)

oppose any
change

induced voltage

$$\mathcal{U}_{emf} = \oint_{\partial \Sigma} \vec{E} \cdot d\vec{\ell} = - \frac{d}{dt} \iint_{\Sigma} \vec{B} \cdot d\vec{S} = - \frac{d\phi}{dt}$$

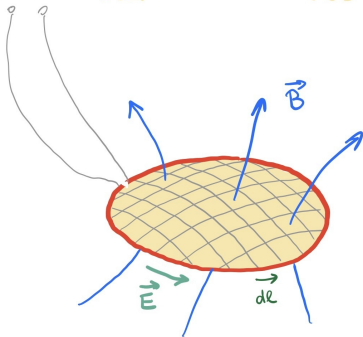


Maxwell–Faraday equation (Faraday's law of induction)

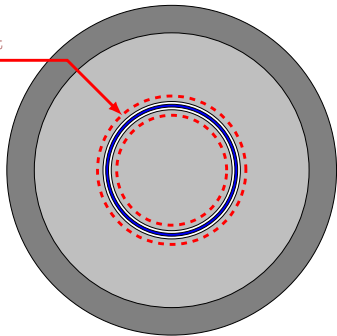
oppose any change
rate of change $\Rightarrow$ frequency $\uparrow$

induced voltage

$$\mathcal{U}_{emf} = \oint_{\partial \Sigma} \vec{E} \cdot d\vec{\ell} = - \frac{d}{dt} \iint_{\Sigma} \vec{B} \cdot d\vec{S} = - \frac{d\phi}{dt}$$



induced eddy currents trying to oppose
any change caused by the voice-coil current



induced voltage results in a current
that we call **eddy current** (ohm's law).

this **eddy current** creates its own magnetic
field that **tries to oppose** the field made by the voice-coil.

The total magnetic flux made by both the voice-coil and the eddy current
is decreased → lower energy, **lower** apparent **inductance**.

experiment n.1

at low frequencies:

R_e remains the same for air and motor

$L_e = \mu \frac{N^2 S}{h}$ is much higher in motor (high permeability μ of iron)

at high frequencies:

R_e in motor increases

L_e in motor decreases

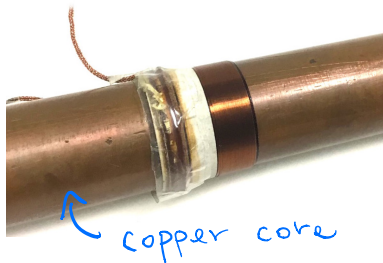


both due to **eddy currents**

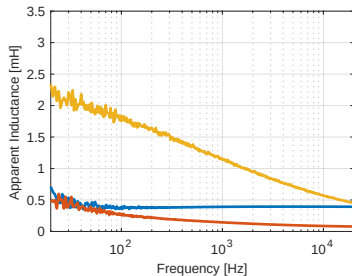
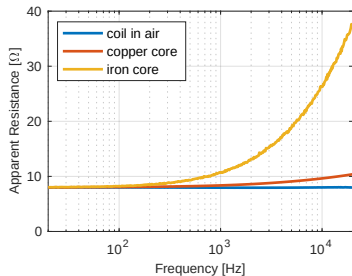
experiment n.2

influence of different voice-coil cores (air, copper, iron)

experiment n.2



experiment n.2



experiment n.2

- voice coil in air

does not exhibit any frequency dependence of apparent resistance or apparent inductance.

- voice coil with a copper core

does exhibit, due to eddy currents, increasing apparent resistance and decreasing apparent inductance with frequency.

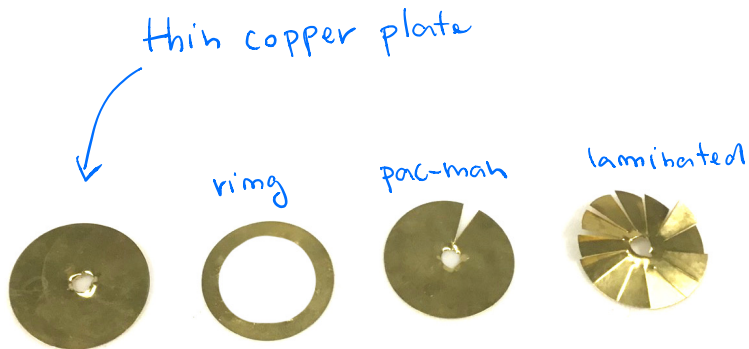
- voice coil with an iron core

does exhibit both the eddy currents (like in previous case) and a much higher inductance due to the high permeability of the core.

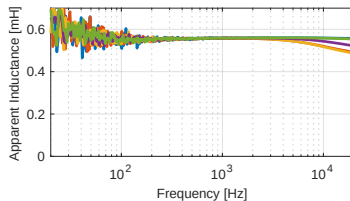
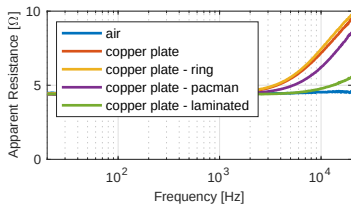
experiment n.3

Thin circular copper plate inside the voice coil

experiment n.3



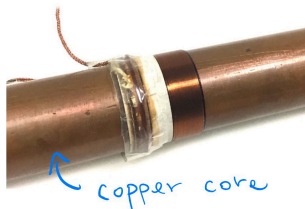
experiment n.3



experiment n.4

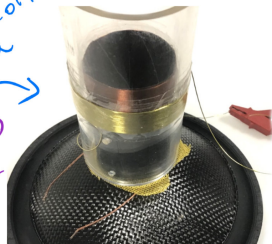
eddy currents transformer behavior

experiment n.4

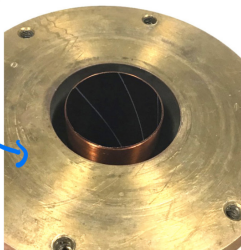


another
(shorted) coil
outside

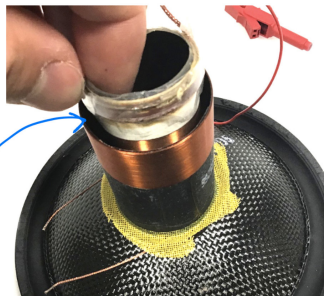
works
like
a transformer



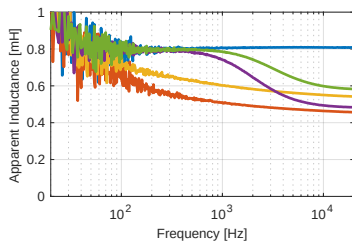
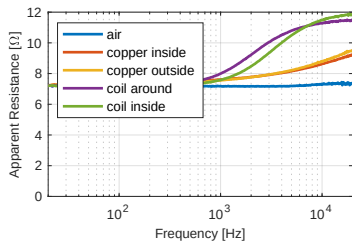
copper ring
outside



another
shorted
coil
inside



experiment n.4



experiment n.4

- voice coil in air

does not exhibit any frequency dependence
of apparent resistance or apparent inductance.

- voice coil with a copper core inside or outside

does exhibit, due to eddy currents, increasing apparent resistance
and decreasing apparent inductance with frequency.

- voice coil and another coil (shorted) inside or outside

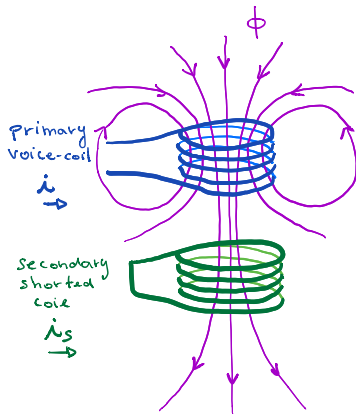
This is to demonstrate that eddy currents behaves as a transformer with
a shorted secondary winding (same principle).

Mutual inductance

a changing current in one coil induces an *emf* in another coil

$$u(t) = R_e i(t) + L_e \frac{di(t)}{dt} - M \frac{di_s}{dt}$$

$$0 = R_s i_s + L_s \frac{di_s}{dt} - M \frac{di(t)}{dt}$$



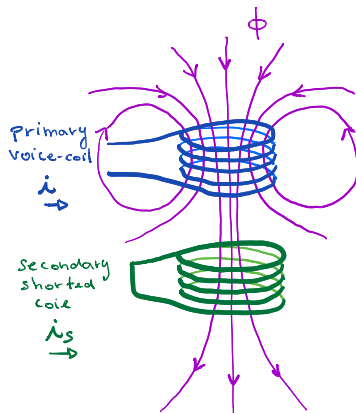
Mutual inductance

... after a little bit of math ...

$$Z_e(\omega) = \frac{U(\omega)}{I(\omega)} = R_e + j\omega L_e + \frac{\omega^2 M^2}{R_s + j\omega L_s}$$

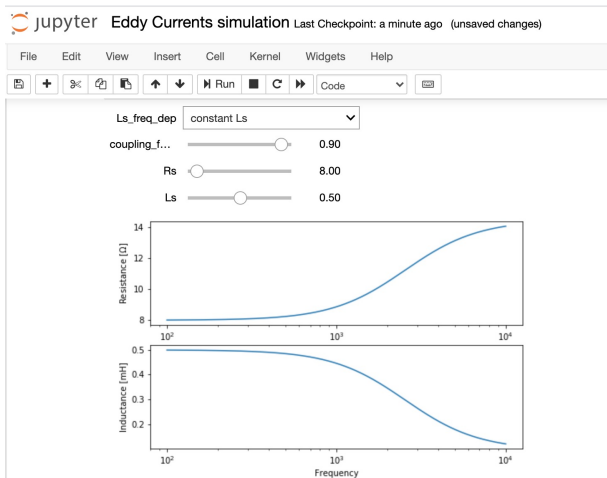
$$\Re\{Z_e(\omega)\} = R_e + \frac{\omega^2 M^2 R_s}{R_s^2 + \omega^2 L_s^2}$$

$$\frac{\Im\{Z_e(\omega)\}}{\omega} = L_e - \frac{\omega^2 M^2 L_s}{R_s^2 + \omega^2 L_s^2}$$



Mutual inductance modeling

Jupyter Notebook file [Eddy_currents_simulation.ipynb](#) on umtice:

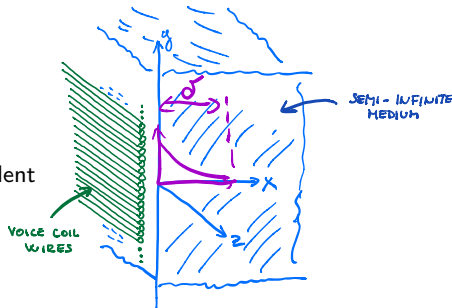


Eddy currents are more complicated than a simple transformer

skin effect in iron: (derived from Maxwell Equations [2])

skin depth $\delta = \sqrt{\frac{2}{\mu\sigma\omega}}$

R_s and L_s are now frequency dependent



- [2] Vanderkooy, J. (1989). A Model of Loudspeaker Driver Impedance Incorporating Eddy Currents in the Pole Structure. J. Audio Eng. Soc., 37(3), 119–128.

What is a shorting ring ?

NRSC (non-resonant suspension coupling) (patented)

NBR Multi-Roll Surround with Edge Reflection Control (patent pending)

Machined Aluminum Phase Plug with Direct Heat Transfer Heat-sink

Hybrid Cross-Rib Glass Fiber Cone

Cast Aluminum Frame

Snap Fit Mounting System

Linearized Nomex/Conex Spider

Insert/Spade Terminals

Vented Spider Landing & Forced Air Heatsink Cooling (patent pending)

Ultra High Temp VC CCAW wire on 39mm Titanium Former

Copper Shorting Ring

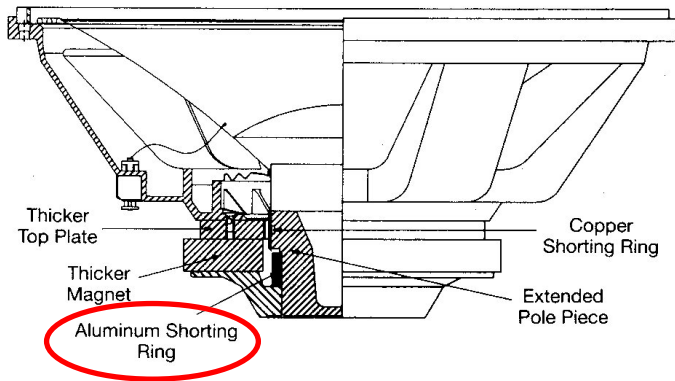
Vented Radial Aluminum Shorting Sleeve and Heat-sink (patent pending)

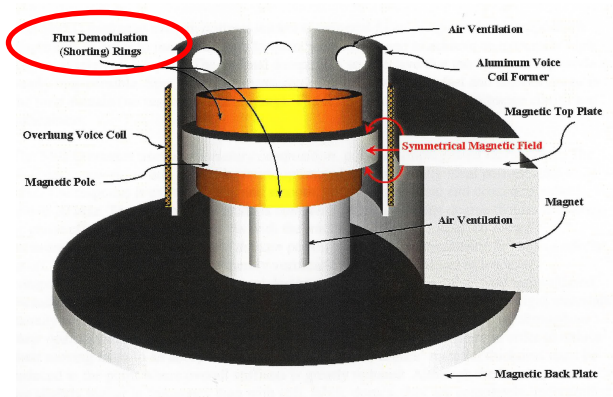
High Grade Neodymium Magnet

Machined Low-Carbon Steel U-Yoke

**Aluminum
Shorting Ring**

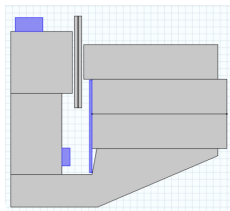
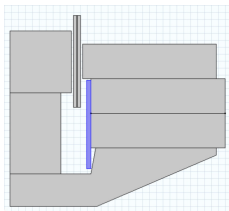
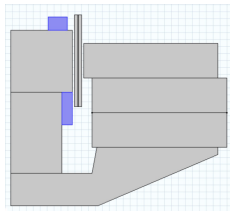
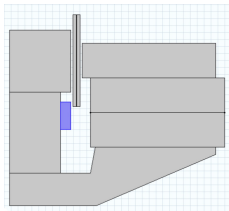






Sony Technical Paper, SS-M9ED speaker, p.272

Examples of shorting ring position



- [1] Bortot, L. (2013). Optimization of demodulation rings in professional loudspeakers. Master Thesis, Università degli Studi di Padova, Italy.

The role of shorting rings :

- 1) increase the **eddy currents**
- 2) **decrease inductance** L_e and linearize $L_e(x)$
- 3) make the magnetic field more symmetric
- 4) decrease flux modulation and linearize $L_e(i)$

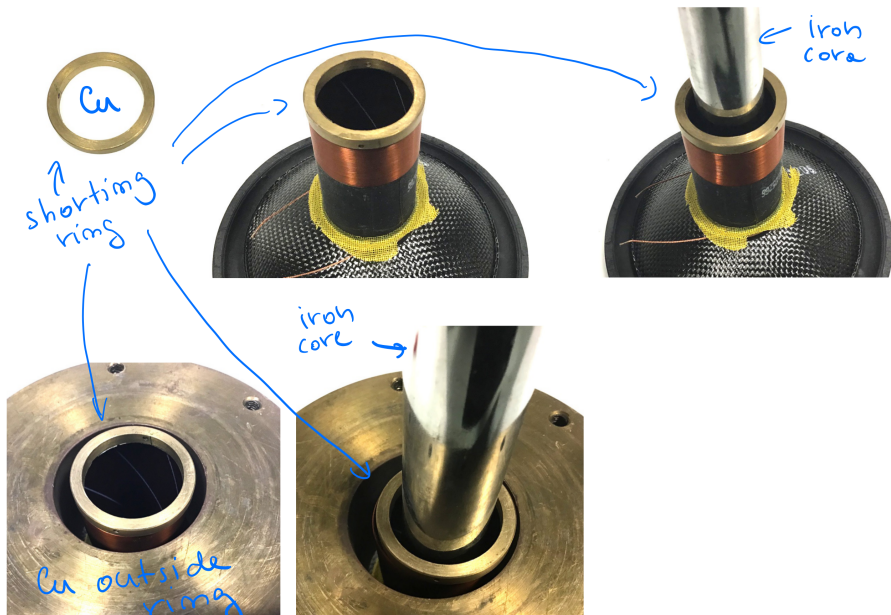
consequently: decrease distortion and increase efficiency

1) increase the **eddy currents**

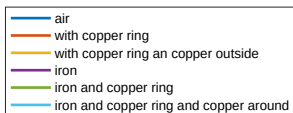
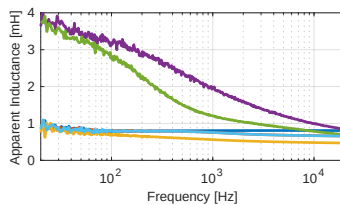
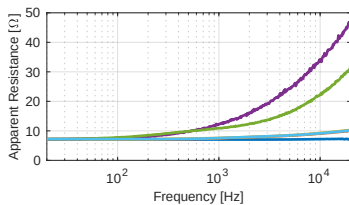
experiment n.5

influence of shorting (copper) rings

experiment n.5



experiment n.5



experiment n.5

This experiment demonstrates that the apparent inductance of a voice-coil inside a motor can be decreased using a copper (or aluminium, or any non-magnetic conductive material) ring.

Shorting rings use the effect of eddy currents.

experiment n.6

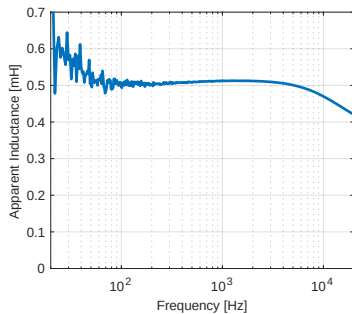
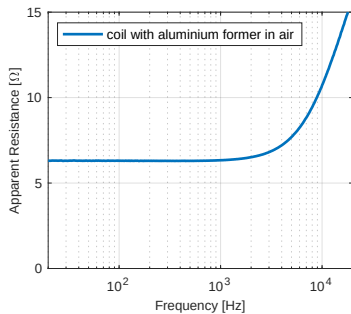
a voice-coil with an aluminium former (not shorted)

experiment n.6

voice-coil with an
aluminium former
not shorted



experiment n.6

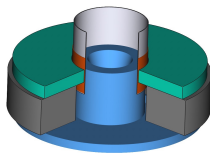


2) decrease inductance L_e and flatten $L_e(x)$

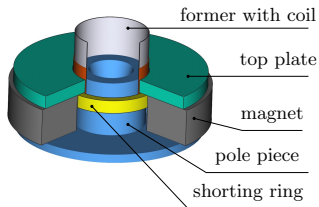
experiment n.7

blocked impedance as a function of coil position

experiment n.7

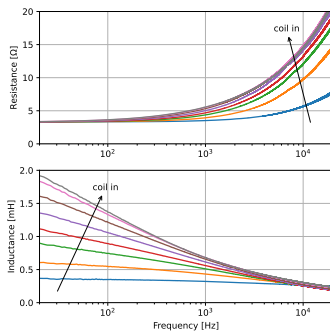
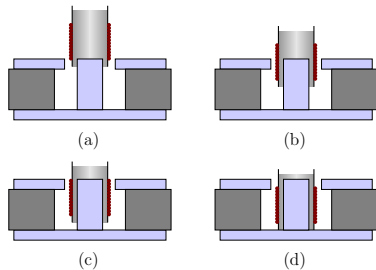


(a) Fital 5FE100

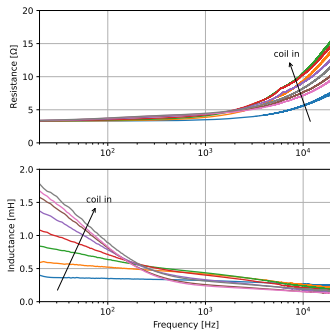
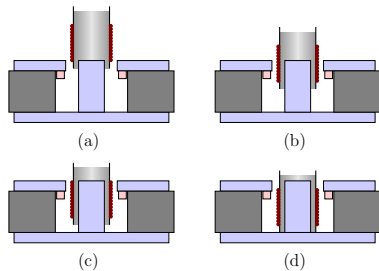


(b) Fital 5FE120

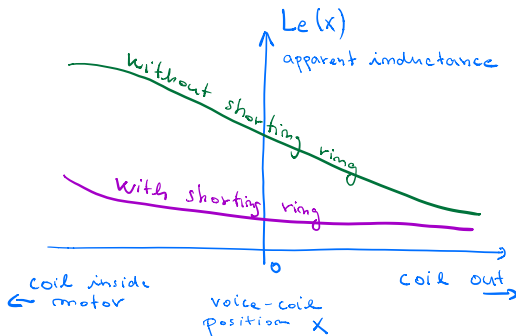
experiment n.7 - normal motor



experiment n.7 - motor with shorting rings



experiment n.7



- **without shorting rings** : strong dependence of $L_e(x)$ on displacement due to the varying amount of iron seen by the coil (different permeability and consequently different inductance) for each position.
- **with shorting rings** : smaller dependence of $L_e(x)$ on displacement. Shorting rings decrease the inductance (due to eddy currents) no matter the position of the voice-coil.

consequence of $L_e(x)$

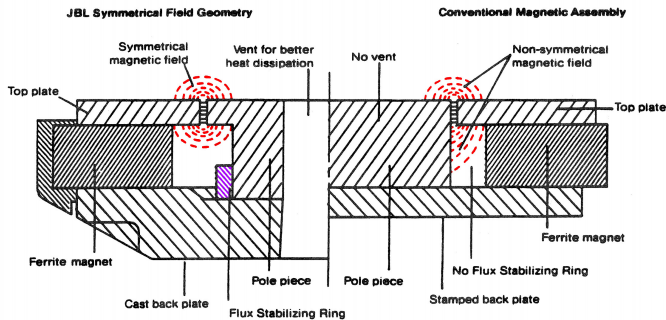
nonlinear distortion

$$u(t) = R_e i(t) + L_e(x) \frac{di(t)}{dt} + Bl v(t)$$

$$u(t) = R_e i(t) + \left(L_{e0} + L_{e1}x(t) + L_{e2}x(t)^2 + \dots \right) \frac{di(t)}{dt} + Bl v(t)$$

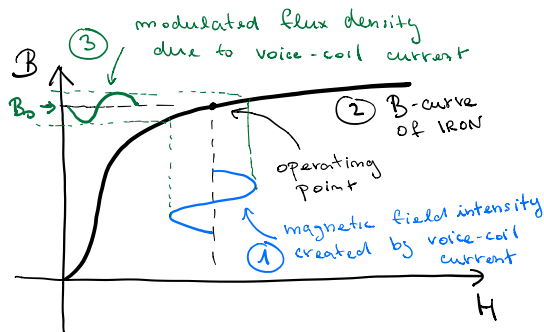
3) make the magnetic field more symmetric

more symmetric magnetic filed



4) decrease flux modulation and linearize $L_e(i)$

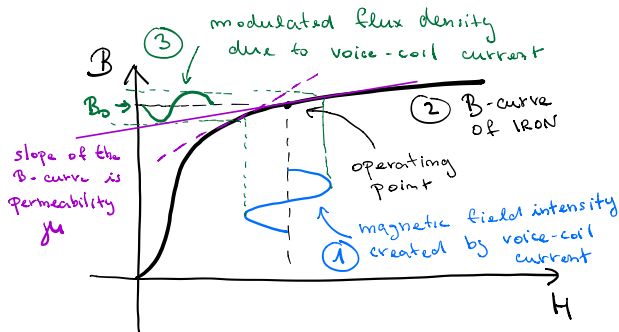
decrease flux modulation and linearize $L_e(i)$



H ... magnetic field intensity (external)

B ... magnetic flux density

decrease flux modulation and linearize $L_e(i)$



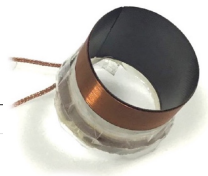
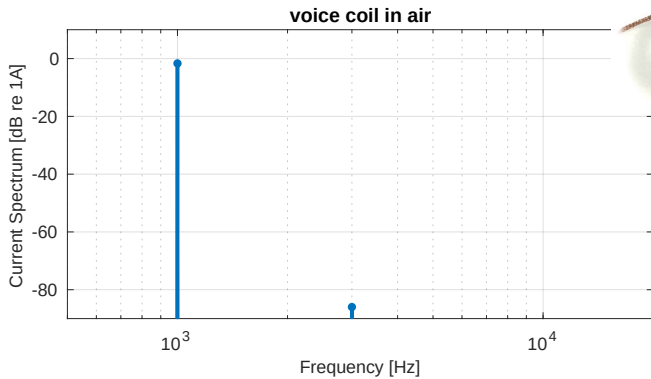
H ... magnetic field intensity (external)

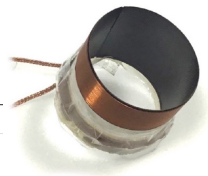
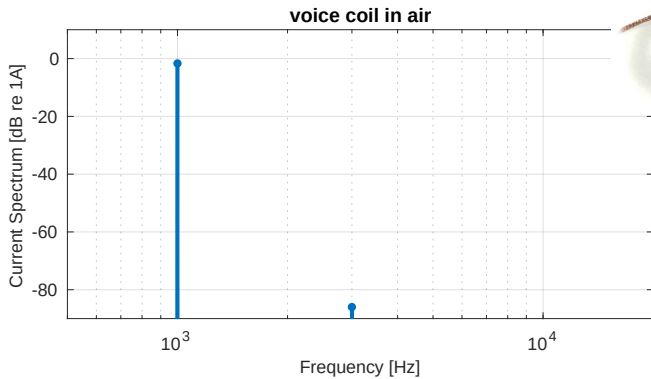
B ... magnetic flux density

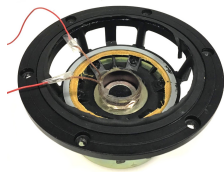
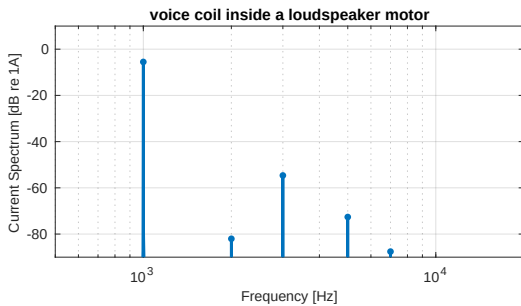
$\mu = \frac{dB}{dH}$... (differential) permeability

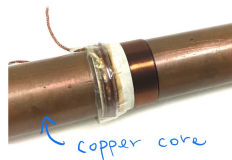
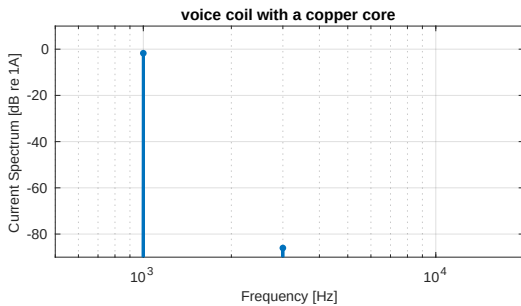
experiment n.8

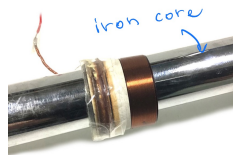
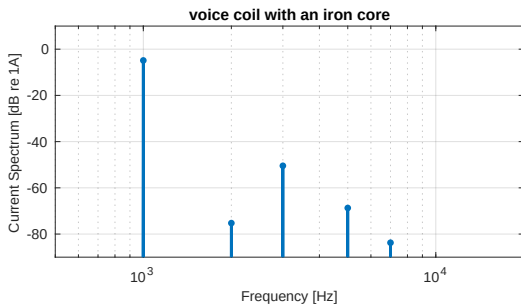
current distortion of blocked voice-coil
(no displacement)

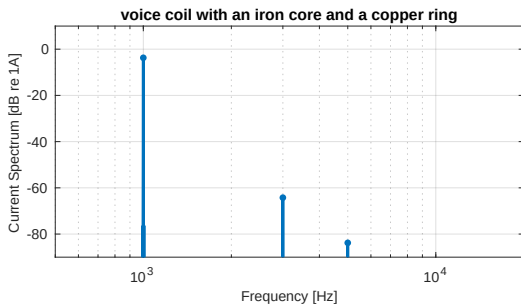




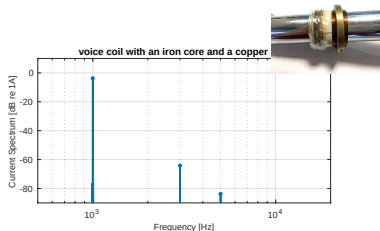
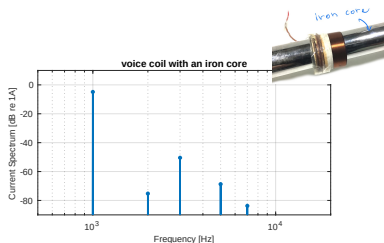








experiment n.8



- voice-coil creates its own magnetic field intensity H_{coil} that tries to magnetize and demagnetize the iron (BH-curve slope changes) $\Rightarrow L_e$ varies with current.
- currents running in shunting rings try to oppose H_{coil} by creating H_{ring}
- in an ideal case $H_{ring} = -H_{coil}$ and the only remaining magnetic field is the one of magnets. $\Rightarrow L_e$ remains constant.
- otherwise $H_{ring} \neq -H_{coil}$ and the remaining magnetic intensity $H_{ring} - H_{coil}$ is lower than in the first case $\Rightarrow L_e$ varies, but less.

thank you for your attention ...