# 1: System to actuator requirements
# 2: Reluctance actuator

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Date:

Version: 0.2

# 2:
# Reluctance type of actuator

# Reluctance actuator

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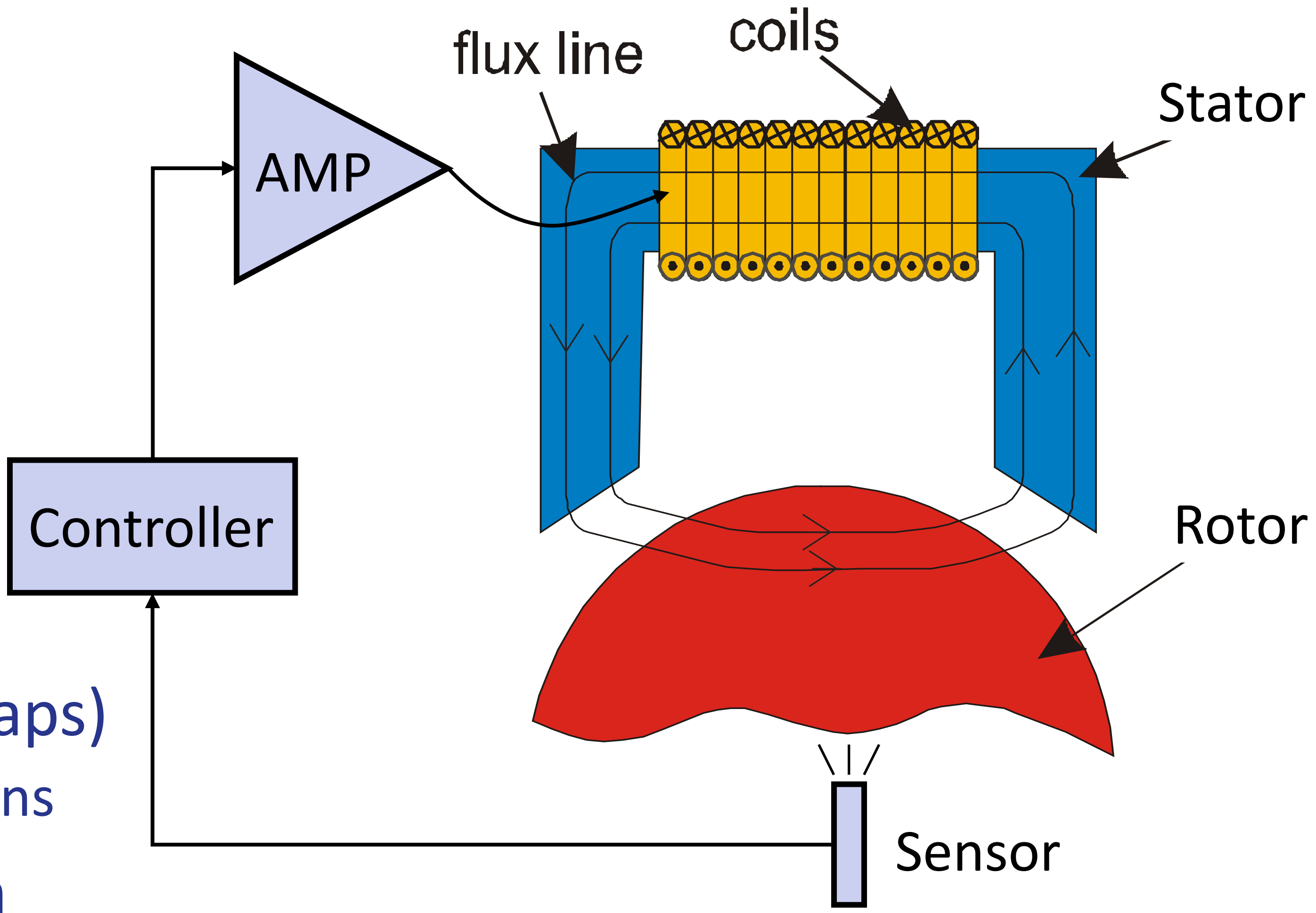


- Large forces (… for small gaps)
  - Used for bearing applications
- Vacuum and/or ultra clean

# References



- References
  - Feynman’s lecture’s on Physics
  - PhD thesis – A. Katalenic
  - PhD thesis – I. MacKenzie
  - PhD thesis – L. Jabben

**Control of reluctance actuators for high-precision positioning**

***Citation for published version (APA):***
Katalenic, A. (2013). *Control of reluctance actuators for high-precision positioning*. Technische Universiteit Eindhoven. https://doi.org/10.6100/IR752336

**Design and control methods for high-accuracy variable reluctance actuators**

by

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at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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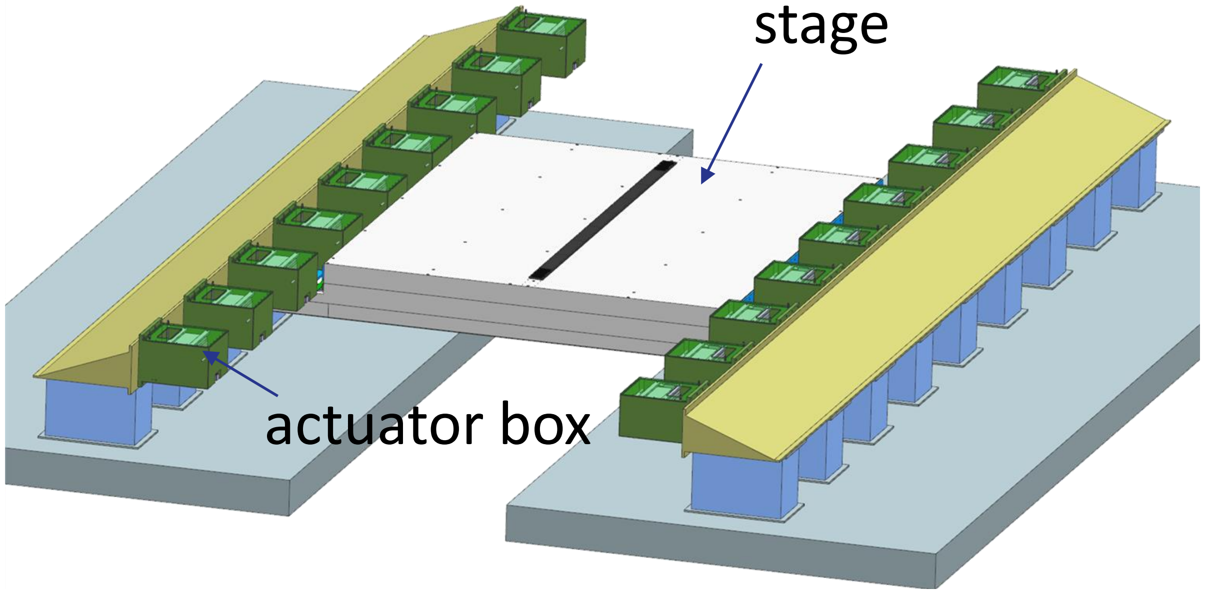
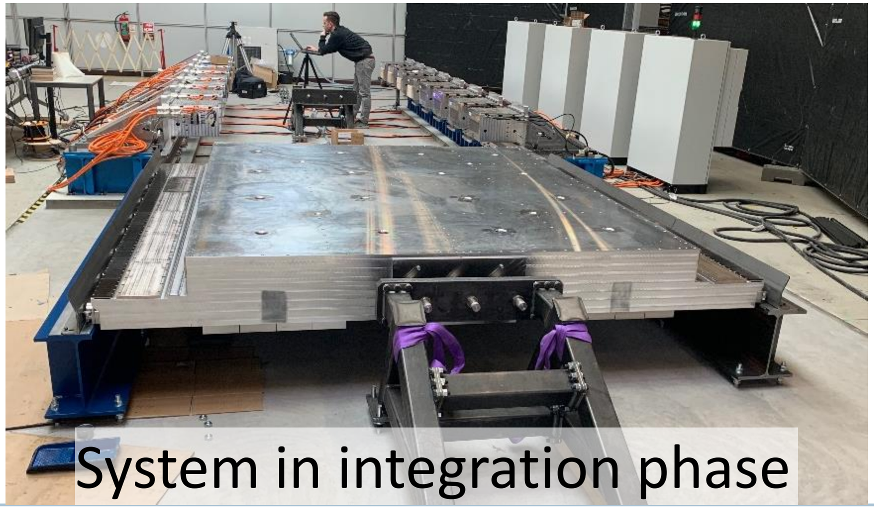
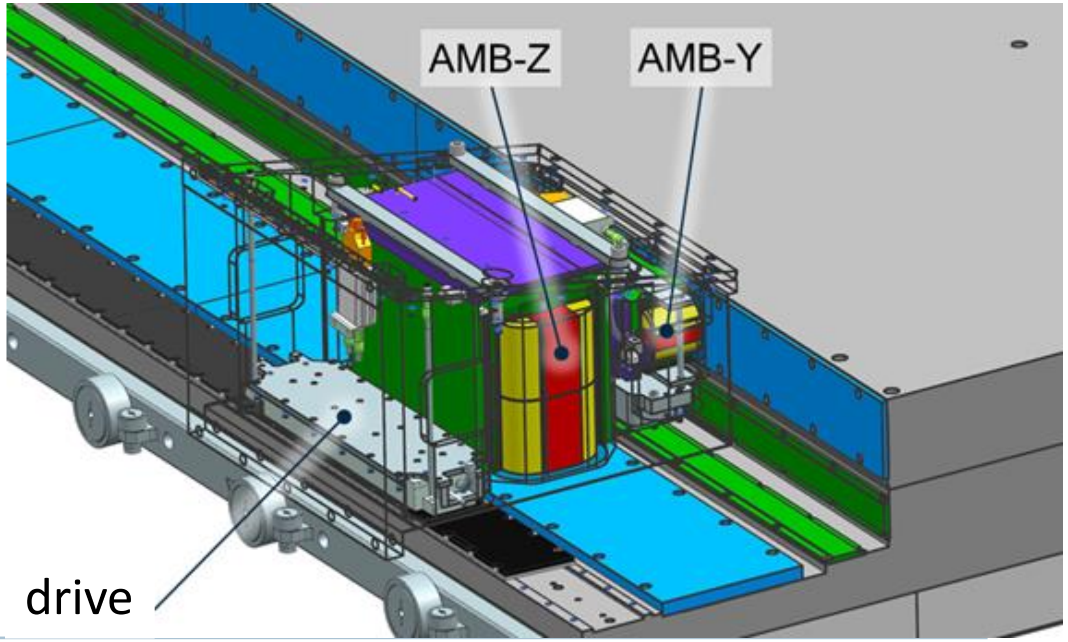
# Magnetic Levitated Transport system




## Challenges :

- Contradicting BW requirements:
  - Big size carrier (3.1x2.7 $m^2$): low dynamics (75 Hz)
  - Negative stiffness from AMB
- Use of industrial standard controllers: local control without decoupling
- Mechanical tolerances vs small gap of MagLev
- Timeline: 9 months to realize test track

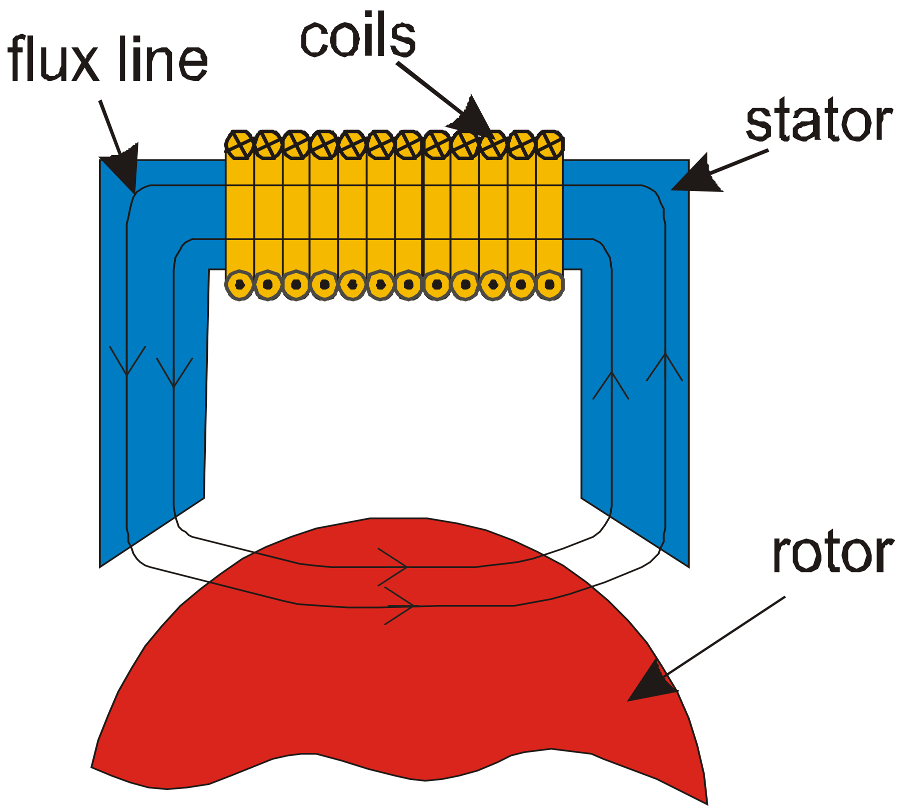


# Magnetic equations for flux density

- Gauss Law: $\nabla \cdot \vec{B} = 0$ or $\oiint_S \vec{B} \cdot d\vec{s} = 0$
  - B: magnetic field (flux density) [T],
- Ampere's Law:

$$\nabla \times \vec{B} = \mu_0(\vec{\rho}_f + \vec{\rho}_m)$$

  - $\mu_0 = 4\pi \cdot 10^{-7}$ N/A$^2$: permeability vacuum
  - $\rho_f$ : free current density [A/m$^2$]
  - $\rho_m$ : magnetization current density [A/m$^2$]
- Magnetization current density: $\vec{\rho}_m = \nabla \times \vec{M}$
- Hence: $\nabla \times \vec{B} = \mu_0(\vec{\rho}_f + \nabla \times \vec{M})$



# Relation Flux density vs magnetic field

- Ampere's Law becomes

$$\nabla \times \vec{B} = \mu_0(\vec{\rho}_f + \nabla \times \vec{M}) \Leftrightarrow \nabla \times \left(\frac{\vec{B}}{\mu_0} - \vec{M}\right) = \vec{\rho}_f$$

- Can define magnetic field (intensity): $\vec{H} \stackrel{\text{def}}{=} \frac{\vec{B}}{\mu_0} - \vec{M} \;\Leftrightarrow\; \vec{B} = \mu_0(\vec{H} + \vec{M})$
- Magnetization is in same direction *H*: $\vec{M} = \chi(x, y, z, H)\vec{H}$ [A/m]
- If the material is
  - linear: $\frac{\partial \chi}{\partial H} = 0$ (ferromagnetic: nope!) and
  - homogeneous: $\frac{\partial \chi}{\partial (x,y,z)} = 0$ (kind of)

$$\left.\begin{array}{l} \\ \\ \end{array}\right\} \quad \vec{B} = \mu_0(1 + \chi)\vec{H} = \mu_0\mu_r\vec{H}$$

# Magnetic circuit

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- Integrating both sides of $\nabla \times \vec{H} = \vec{\rho}_f$ over area and using Green's theorem:

$$\iint_A \nabla \times \vec{H} \cdot d\vec{a} = \oint_{\partial A} \vec{H} \cdot d\vec{l} = \iint_A \vec{\rho}_f \cdot d\vec{a}$$

- Current is confined to wire: $\iint_A \vec{\rho}_f \cdot d\vec{a} = n_c i$ ($n_c$ : number of turns)
- Total flux through a surface: $\Phi = \iint_A \vec{B} \cdot d\vec{a}$
- Break up circuit in "tubes" of same material, no flux leaving sides of tubes:

$$n_c i = \oint_{\partial A} \vec{H} \cdot d\vec{l} = \sum_k H_k l_k = \sum_k \frac{B_k l_k}{\mu_0 \mu_k} = \Phi \sum_k \frac{l_k}{A_k \mu_0 \mu_k} = \Phi \mathcal{R}_m$$

  - $R_m$ is the magnetic resistance [A/T/m$^2$]

# Magnetic energy

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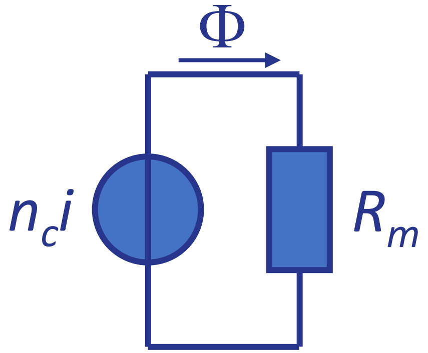
- We have developed a magnetic analogue to simple electric circuit
  - But no flow of power carrying particles ⇒ no dissipation!
  - Magnetic flux less confined by circuit than current
- Inductance of the coil:

$$\lambda = n_c\Phi = Li = \frac{n_c^2}{\mathcal{R}_m} i \Longrightarrow L = \frac{n_c^2}{\mathcal{R}_m}$$

- Magnetic energy: $E_m = \frac{1}{2}Li^2$
- Force on moveable part:

$$F = \frac{\partial E_m}{\partial x} = \frac{1}{2}i^2\frac{\partial L}{\partial x} = -\frac{1}{2}\frac{i^2 n_c^2}{\mathcal{R}_m^2}\frac{\partial \mathcal{R}_m}{\partial x}$$




$$u_{MMF} = n_c i = \Phi\mathcal{R}_m$$

MMF: MagnetoMotive Force

# Magnetic circuit Modelling

- Total Magnetic resistance:

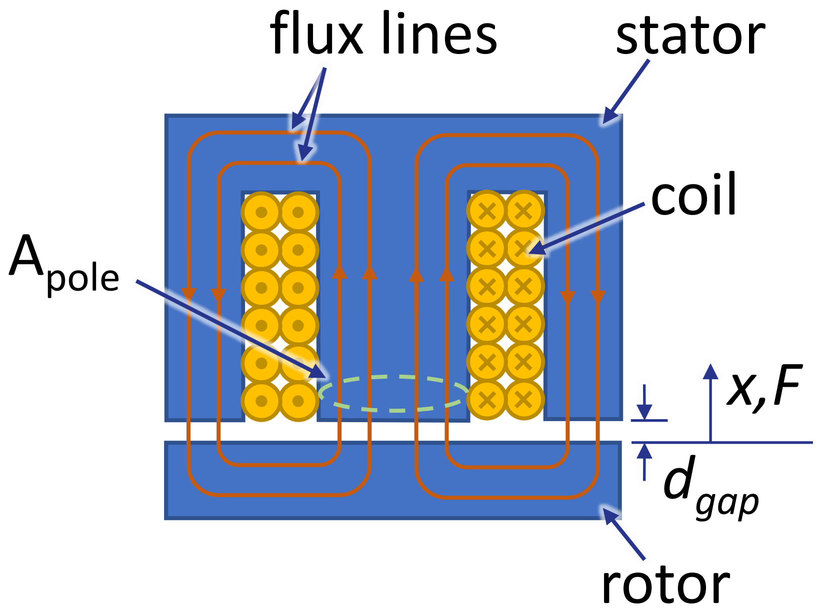
$$\mathcal{R}_m(x) = \frac{1}{A_{pole}\mu_0}\left(\frac{l_{iron}}{\mu_{iron}} + \frac{2(d_{gap}-x)}{\mu_{air}}\right),$$

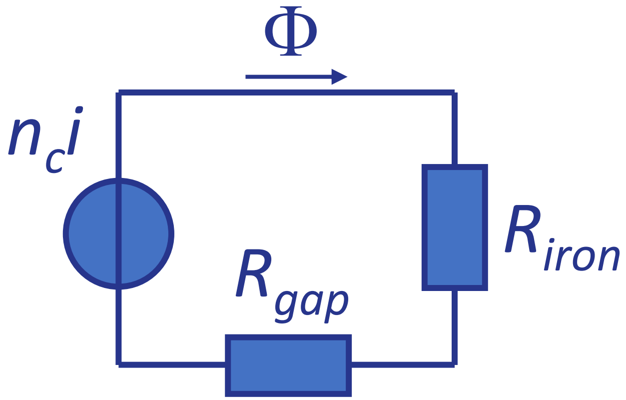
- Hence, attraction force on rotor:

$$F = -\frac{1}{2}\frac{i^2 n_c^2}{\mathcal{R}_m^2}\frac{\partial \mathcal{R}_m}{\partial x} = \frac{n_c^2 i^2}{\mu_{air}\mu_0 A_{pole}\mathcal{R}_m^2}$$

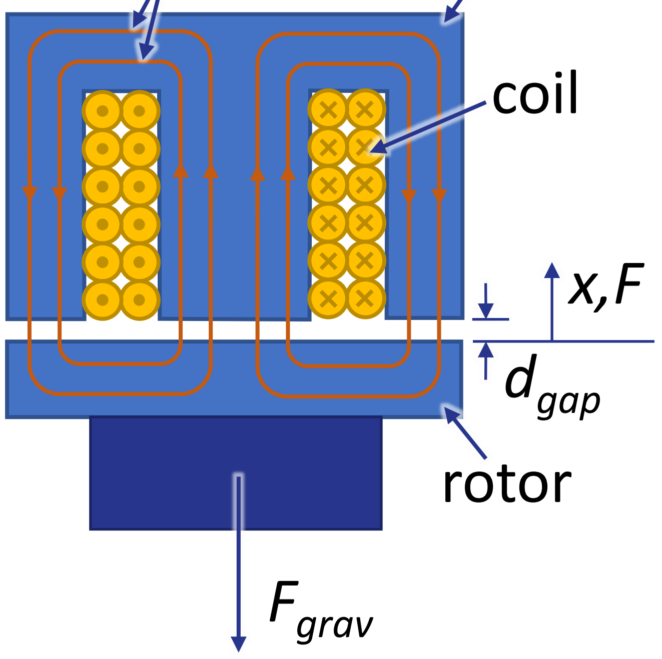
- Can simplify: $\mu_{air} \approx 1$, $\mu_{iron} \approx 4000 \Rightarrow \frac{l_{iron}}{\mu_{iron}} \ll \frac{2d_{gap}}{\mu_{air}} \Rightarrow$

$$F \approx \frac{1}{4}\mu_0 n_c^2 A_{pole}\frac{i^2}{x_{gap}^2} = k_{ra}\frac{i^2}{x_{gap}^2}$$ (using: $x_{gap} = d_{gap} - x$)



# Linearizing with gravity





- With zero current we have zero force… but also $\left.\frac{\partial F}{\partial i}\right|_{i=0} = 0$
  - Need to preload actuator (gravity, other RA, permanent magnet)
- With $i_0$ the current needed to generate $F_{grav}$:

$$F = k_{ra}\frac{(i_0+i)^2}{\left(d_{gap}-x\right)^2}$$

- Linearize around $i=0$ & $x=0$

$$F = \frac{\partial F}{\partial i}i + \frac{\partial F}{\partial x}x = 2k_{ra}\frac{i_0}{d_{gap}^2}i + 2k_{ra}\frac{i_0^2}{d_{gap}^3}x$$

# Linearizing with two opposite RAs

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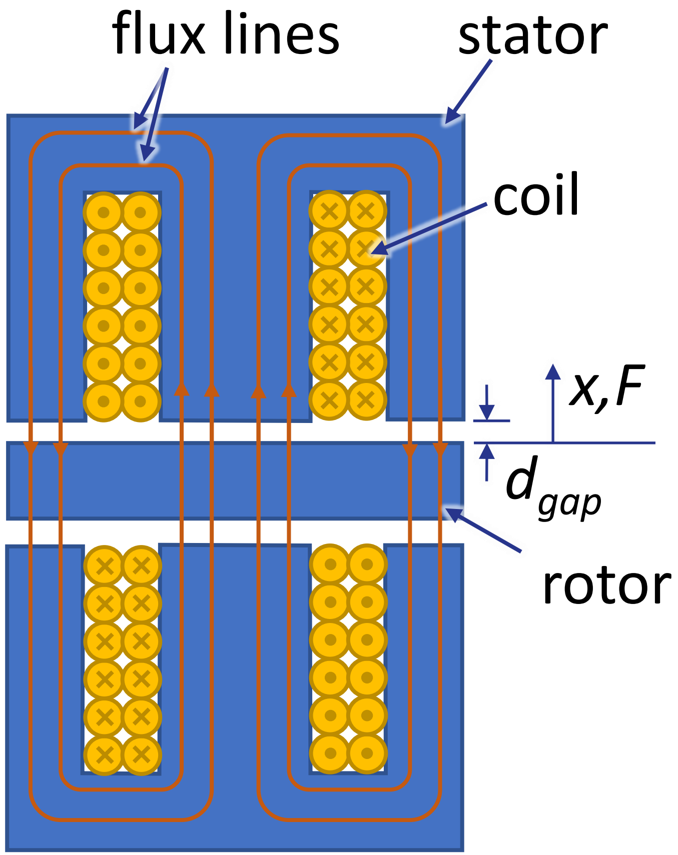
- Two opposite RAs (often used)

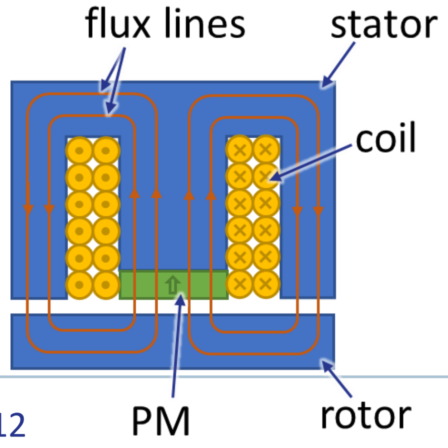
$$F = k_{ra}\frac{(i_0+i)^2}{(d_{gap}-x)^2} - k_{ra}\frac{(i_0-i)^2}{(d_{gap}+x)^2}$$

- Linearize around *i=0* & *x=0*

$$F = \frac{\partial F}{\partial i} i + \frac{\partial F}{\partial x} x = 4k_{ra}\frac{i_0}{d_{gap}^2} i + 4k_{ra}\frac{i_0^2}{d_{gap}^3} x$$

- For completeness: a permanent magnet can also be used for preloading
    - Less thermal dissipation!



# Magnetic "pressure"

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- Recall: $F = \dfrac{n_c^2 i^2}{\mu_{air}\mu_0 A_{pole}\mathcal{R}_m^2}$
- With $n_c i = \Phi\mathcal{R}_m$ and $\Phi = BA_{pole}$ the force becomes:

$$F = \frac{A_{pole}\mathrm{B}^2}{\mu_0} \Leftrightarrow \frac{F}{A_{pole}} = \frac{\mathrm{B}^2}{\mu_0}$$

- Note that
  - the total iron surface is twice the surface of the pole
  - the total surface of the actuator is bigger because of the coil: take another factor 2
- With flux density of 0.5-1.0 T, the "pressure" becomes:

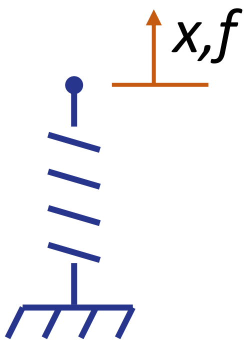
$$\frac{F}{A_{act}} = \frac{\mathrm{B}^2}{4\mu_0} = \frac{\mathrm{B}^2}{4 \cdot 4\pi \cdot 10^{-7}} \approx 5 - 20\ N/cm^2$$ (0.5-2 bar)

# Position coupling: stiffness

- Recall:

$$F = 2k_{ra}\frac{i_0}{d_{gap}^2}i + 2k_{ra}\frac{i_0^2}{d_{gap}^3}x$$

- Positional coupling… Not good in metro-force frame machine concepts
- Even worse, the coupling is actually a negative stiffness!
  - Open loop is unstable!
- Rewrite above as: $F = k_i i - k_x x$, with $k_x = -2k_{ra}\frac{i_0^2}{d_{gap}^3}$
- With bias force: $F_0 = k_{ra}\frac{i_0^2}{d_{gap}^2}$, hence $k_x = -2\frac{F_0}{d_{gap}}$




With displacement $x$, a mechanical spring exerts a force: $f = -kx \Rightarrow$ stable!

# Respect the unstable…

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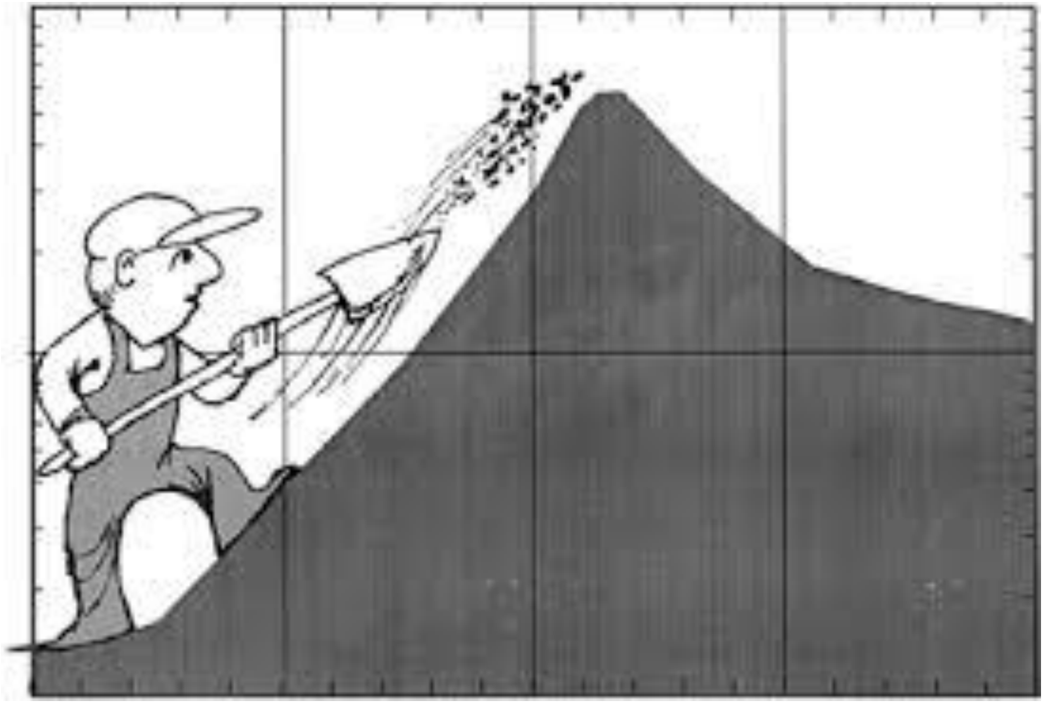
- Gunter Stein, "Respect the Unstable" :
  - Unstable plants are fundamentally more difficult to control
  - Controllers for unstable plants are operationally critical
  - Closed loops with unstable plants are only locally stable
- Bode integral:
  - With *S(jω)*: sensitivity function of closed loop system
  - Stable plants: $\int_0^\infty \ln|S(j\omega)|d\omega = 0$
  - Unstable: $\int_0^\infty \ln|S(j\omega)|d\omega = \pi \sum_{p \in P} Re(p)$

Go find it on YouTube

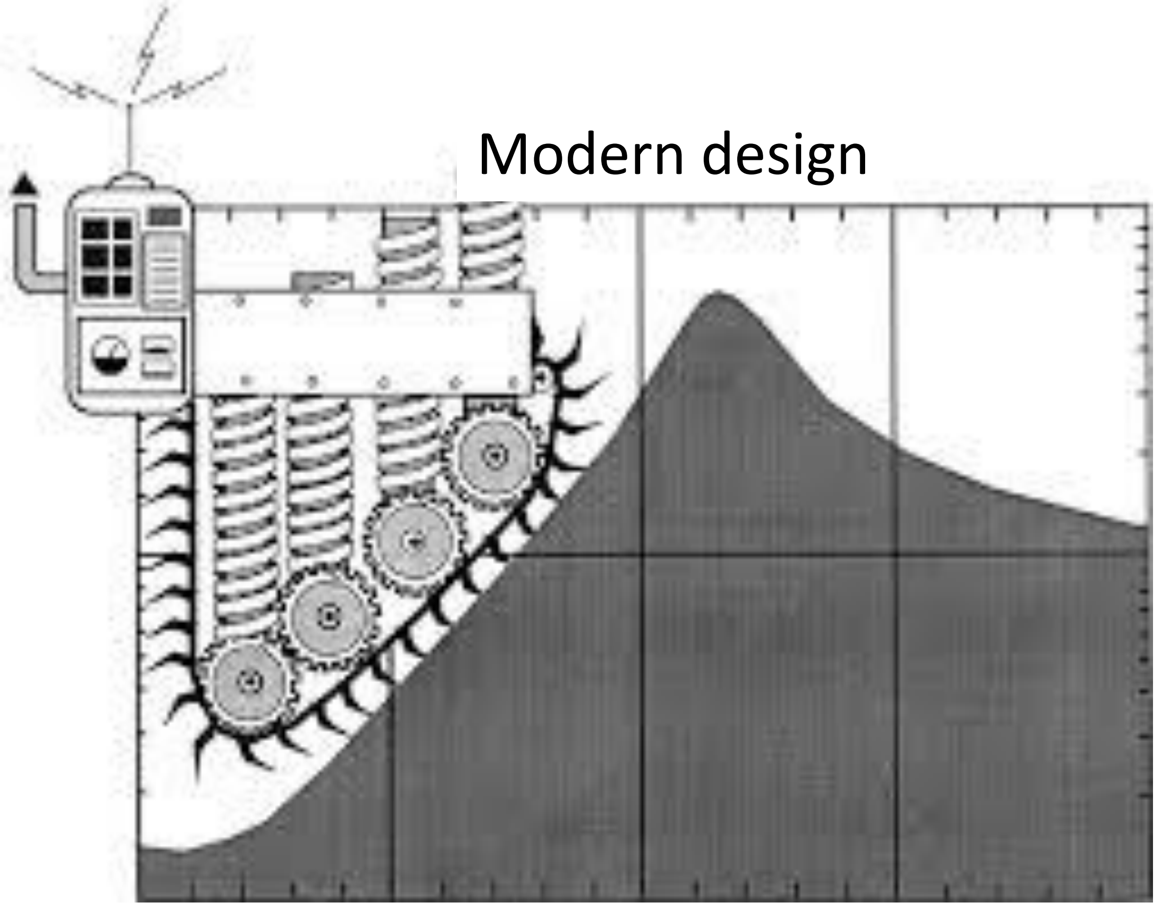
# Controller synthesis (from G. Stijn)

- Conservation law… What is conserved?
  - $\ln|S(j\omega)|$… aka "dirt"

Classic design

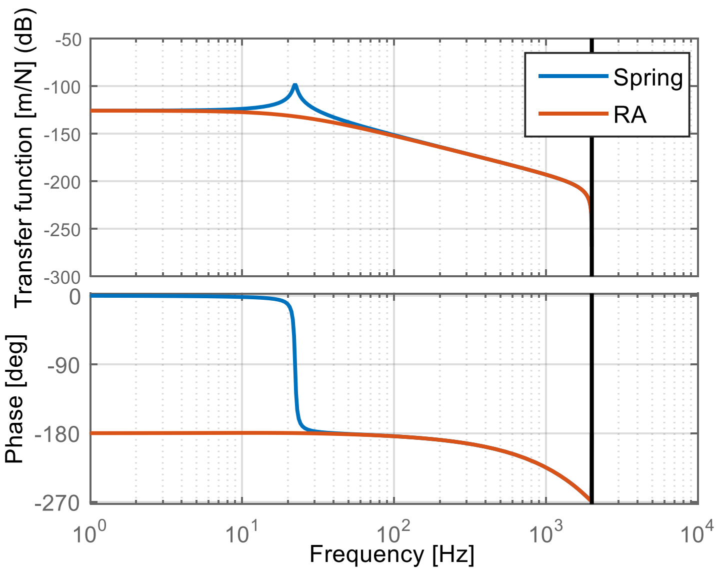


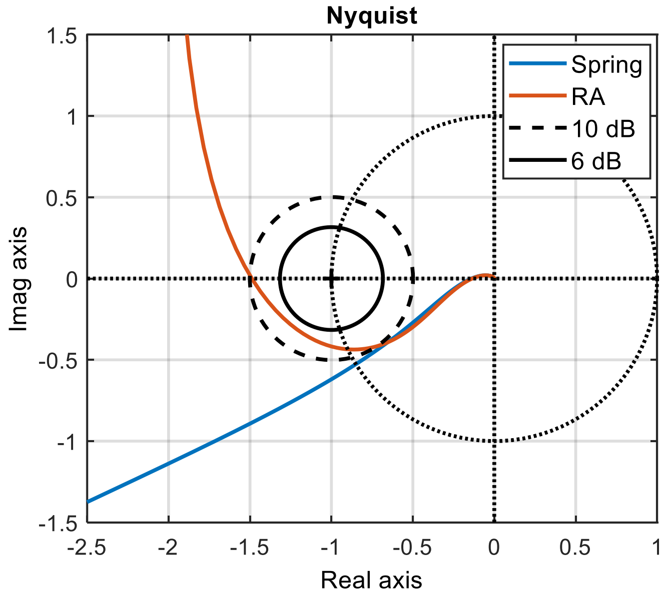
Modern design

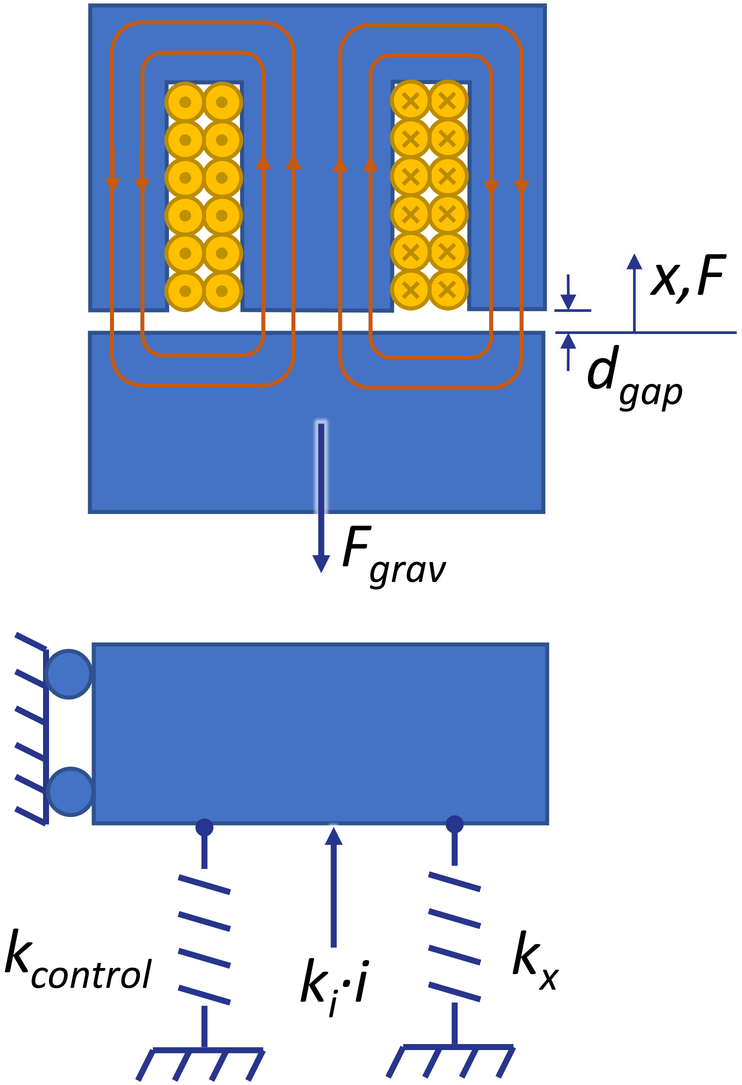


# Example

- Here: $k_x = -2\frac{F_0}{d_{gap}} = -2\frac{mg}{d_{gap}}$, with $g$=9.81 m/s$^2$
- Ignoring minus sine: $\omega_{neg}^2 = \frac{k_x}{m} = 2\frac{g}{d_{gap}}$.
- Air gap of 1mm ⇒ $f_{neg}$= 22 Hz ⇒ Take $f_{bw}$ = 50 Hz
  - Standard PID controller



# Sensitivity of example

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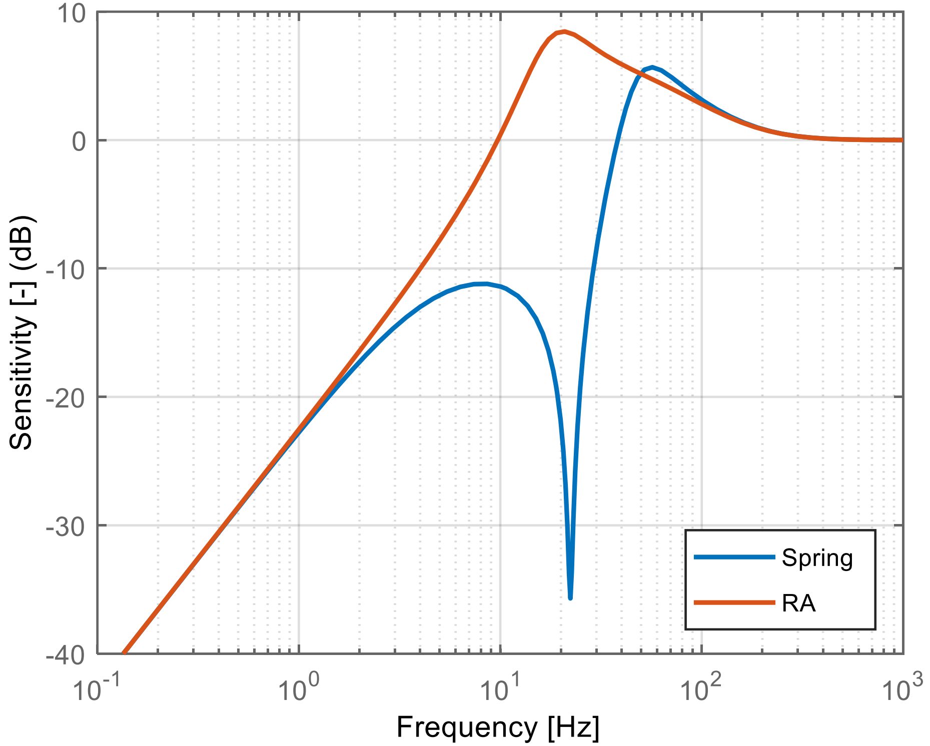
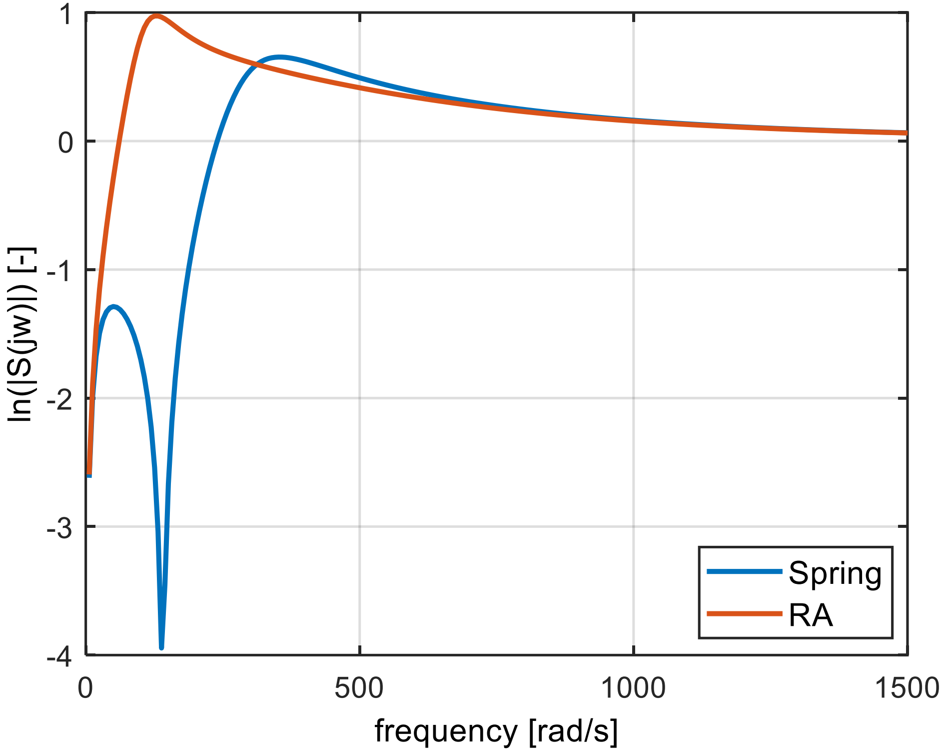
common representation




"Dirt" on linear scales

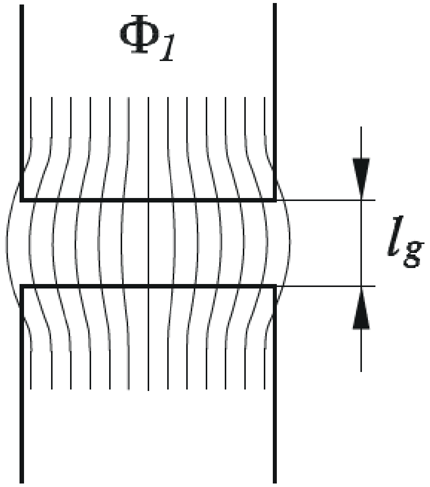


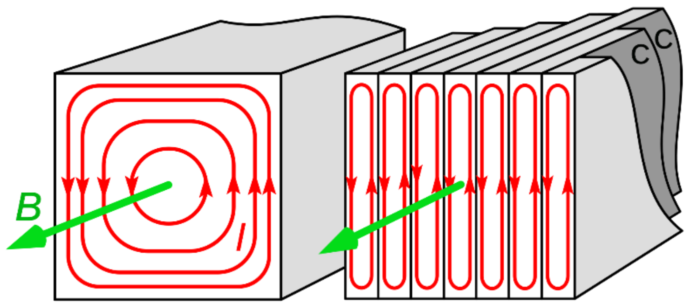

Stable: $\int_0^{\Omega_{lim}} \ln|S(j\omega)| d\omega = \delta = 14$

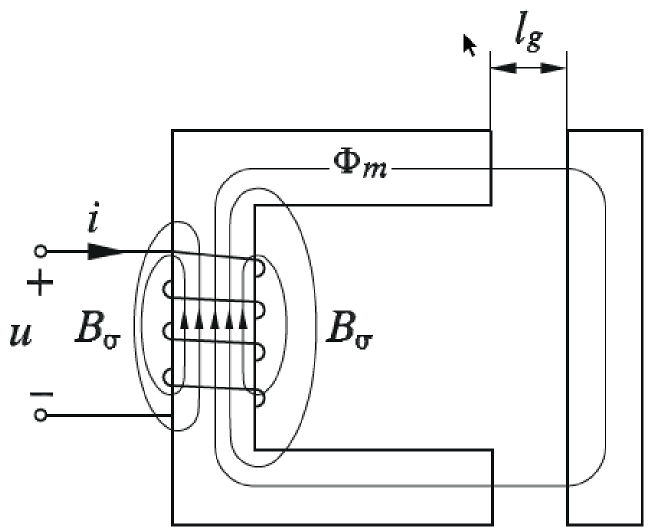
Unstable: $\int_0^{\Omega_{lim}} \ln|S(j\omega)| d\omega = \delta + \pi \sum_{p \in P} Re(p) = 445 \approx 14 + \pi(2\pi 22)$

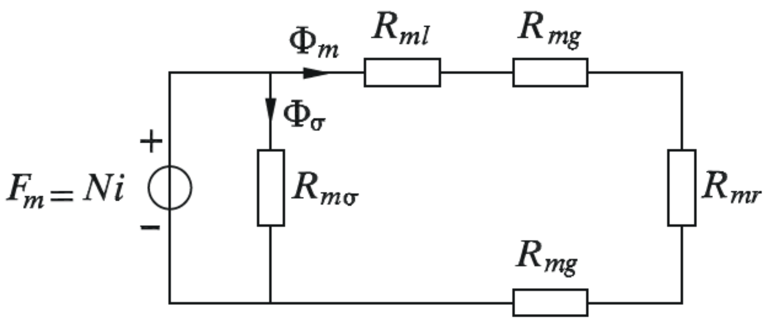
# Practical phenomena (1)

- Fringing of flux
  - Effective pole area becomes bigger
- Leakage flux
  - Less flux through gap ⇒ less force
- Eddy currents
  - $\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$
  - Use laminations



# Practical phenomena (2): Hysteresis

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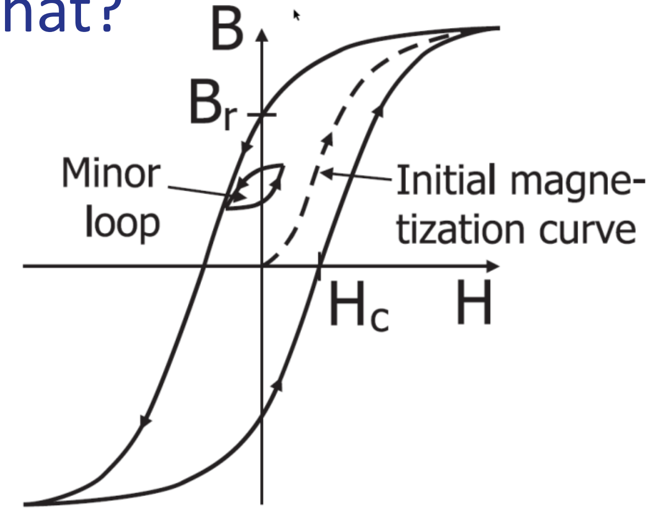
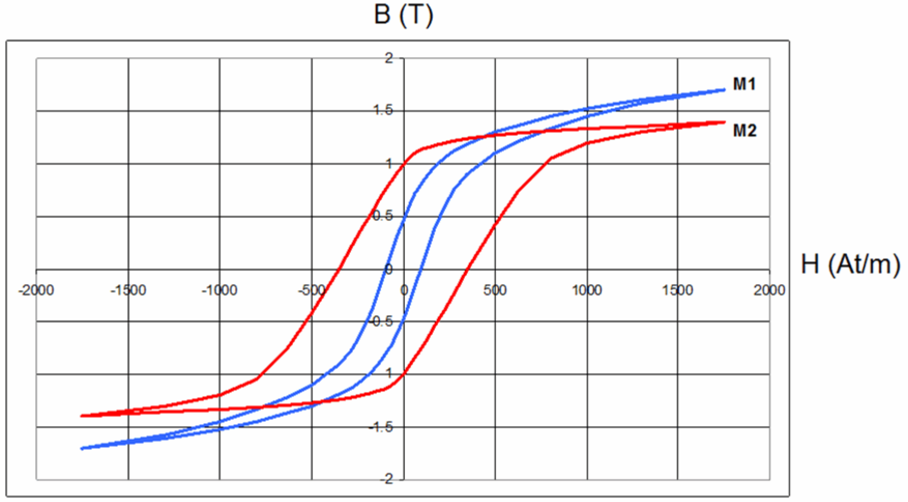
- Recall $\vec{B} = \mu_0(1+\chi)\vec{H} = \mu_0\mu_r\vec{H}$, valid for linear material: $\frac{\partial\chi}{\partial H} = 0$
- Guess what?



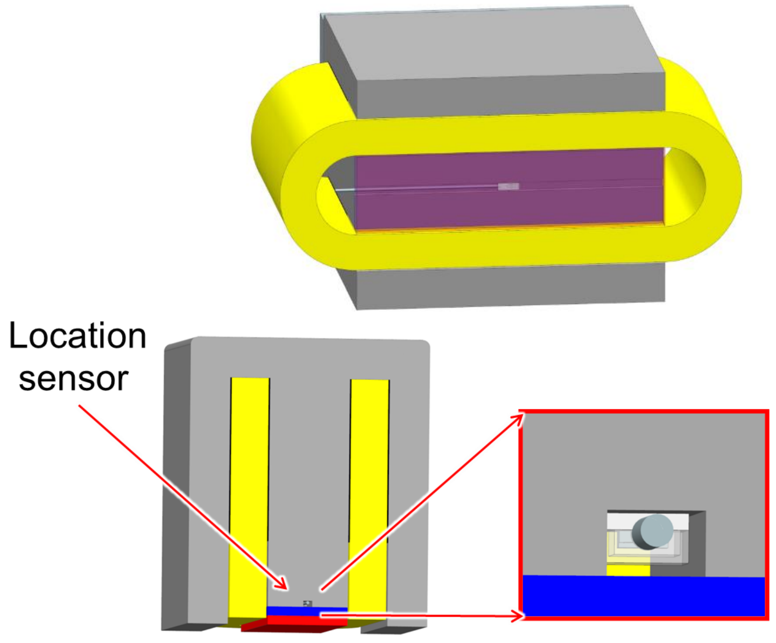




M1 = Silicon Steel, low hysteresis losses (small enclosed area)
M2 = Permanent Magnet, high hysteresis losses (larger enclosed area)
Br of M2 > Br of M1

- Relative permeability goes to one (becoming “air”) when saturating
- Energy loss when cycling through hysteresis loop
- Some phase loss in frequency domain

# Benefits of flux control

- Benefits of flux control
  - Negative stiffness is much reduced: $F = \frac{A_{pole}\mathrm{B}^2}{\mu_0}$
    - Due to flux fringing some  remains
  - Effects of hysteresis is much reduced through the feedback loop
  - Phase loss of eddy currents is much reduced
- The price to pay
  - Additional sensor
  - Which is usually in the air gap (decreasing efficiency)
  - No off-the-shelf amplifiers available



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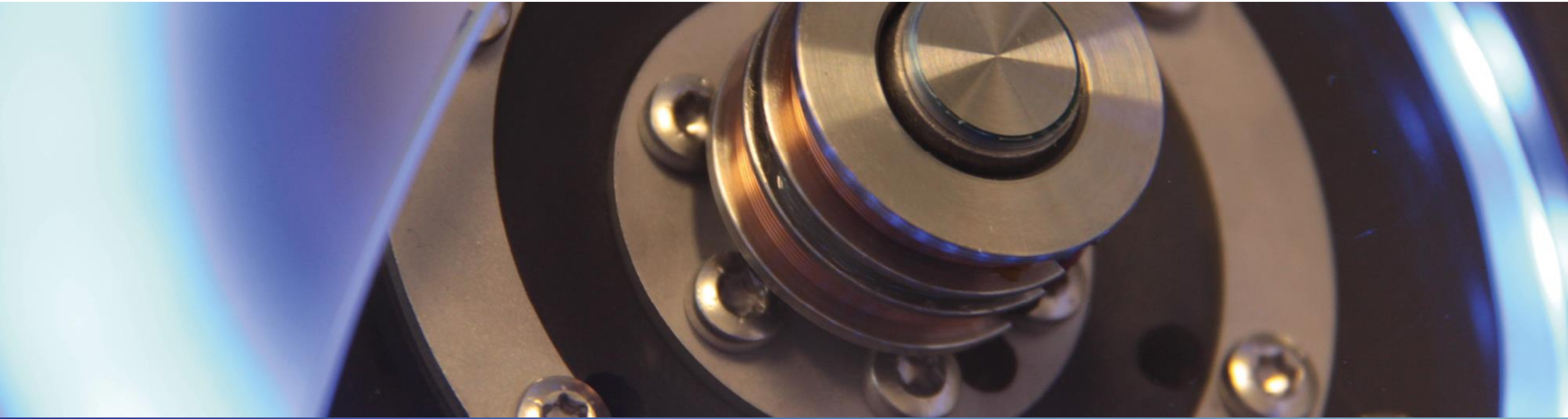

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