Magnetism

The atomic moments add up to produce a total magnetic moment for the permanent magnet, and the magnetization M is the total magnetic moment per unit volume. The ***magnetic flux density*** B seen within the magnet is the result of the driving force of the externally applied magnetic force H and that resulting from the internal magnetization M. On an area-independent basis the ***flux density*** B in the magnet is given by:

$$B = \mu_0 (H+M)$$

Here μ_0 is an arithmetical constant and we have neglected shape-dependent demagnetization effects which may occur.

Magnetic susceptibility and permeability

In large class of materials, there exists a linear relation between M (internal magnetization) and H (external applied magnetic field)

$$M = \chi H$$

χ is positive then the material is called *paramagnetic*

χ is negative then the material is *diamagnetic*

A linear relationship also occurs between B (magnetic flux density) and H (external applied magnetic field)

$$B = \mu H = \mu_o (1+\chi) H = \mu_o(M+H)$$

magnetic permeability is

$$\mu = (1+\chi) \mu_o = \mu_r \mu_o$$

Where μ_r = relative permeability and μ_o = free space permeability

$\mu_r \sim 1$ for paramagentic and diamagnetic, $\mu_r >> 1$ for ferromagnetic.

Permeability

Permeability is defines as

$\mu = (1+\chi)\,\mu_o = \mu_r\,\mu_o$

Where μ_r is relative permeability. χ is susceptibility. Typical values for ordinary liquids and solids are in the range $\mu_r = 1.00001$ to 1.003.

– $\mu_r = 1$ when the material does not respond to the magnetic field by magnetizing.
– $\mu_r > 1$ implies material magnetizes in response to the applied magnetic field.

Susceptibility of diamagnetic and paramagnetic materials

Material	χ_m
Aluminum	2.3×10^{-5}
Copper	-0.98×10^{-5}
Diamond	-2.2×10^{-5}
Tungsten	6.8×10^{-5}
Hydrogen (1 atm)	-0.21×10^{-8}
Oxygen (1 atm)	209.0×10^{-8}
Nitrogen (1 atm)	-0.50×10^{-8}

If χ is positive then the material is called *paramagnetic*, and the magnetic field is strengthened by the presence of the material.
if χ is negative then the material is *diamagnetic*, and the magnetic field is weakened in the presence of the material.

Material	χ_m (x 10^{-5})
Paramagnetic	
Iron aluminum alum	66
Uranium	40
Platinum	26
Aluminum	2.2
Sodium	0.72
Oxygen gas	0.19
Diamagnetic	
Bismuth	-16.6
Mercury	-2.9
Silver	-2.6
Carbon (diamond)	-2.1
Lead	-1.8
Sodium chloride	-1.4
Copper	-1.0

Paramagnetic Materials

Some materials exhibit a magnetization which is proportional to the magnetic flux density in which the material is placed. These materials are said to be paramagnetic and follow Curie's law:

$$M = C(B/T)$$

Where M = magnetization, C= Curie's constant, B=magnetic flux density, T= temperature

All atoms have inherent sources of magnetism because electron spin contributes a magnetic moment and electron orbits act as current loops which produce a magnetic field. In most materials the magnetic moments of the electrons cancel, but in materials which are classified as paramagnetic, the cancellation is incomplete.

Diamagnetic Materials

The orbital motion of electrons creates tiny atomic current loops, which produce magnetic fields. When an external magnetic field is applied to a material, these current loops will tend to align in such a way as to oppose the applied field. This may be viewed as an atomic version of Lenz's law. (Induced magnetic field, once it's there, it will stays)

Ferromagnetic materials

Ferromagnetic materials exhibit a long-range ordering phenomenon at the atomic level which causes the unpaired electron spins to line up parallel with each other in a region called a domain. Within the domain, the magnetic field is intense, but in a bulk sample the material will usually be unmagnetized because the many domains will themselves be randomly oriented with respect to one another.

When small externally imposed magnetic field, say from a solenoid, can cause the magnetic domains to line up with each other and the material is said to be magnetized. The driving magnetic field will then be increased by a large factor which is usually expressed as a relative permeability for the material.

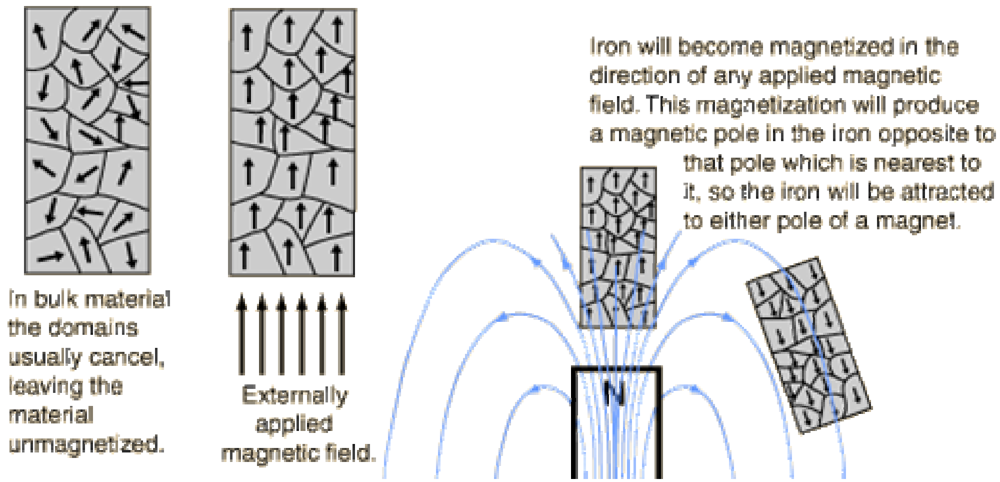
Long Range Order in Ferromagnets

The long range order which creates magnetic domains in ferromagnetic materials arises from a quantum mechanical interaction at the atomic level. This interaction is remarkable in that it locks the magnetic moments of neighboring atoms into a rigid parallel order over a large number of atoms inspites of the thermal agitation which tends to randomize any atomic-level order.

For a given ferromagnetic material the long range order abruptly disappears at a certain temperature which is called the Curie temperature for the material. The Curie temperature of iron is about 1043 K (lower than melting temperature)

Magnetic Domains

The microscopic ordering of electron spins characteristic of ferromagnetic materials leads to the formation of regions of magnetic alignment called domains.



The main implication of the domains is that there is already a high degree of magnetization in ferromagnetic materials within individual domains, but that in the absence of external magnetic fields those domains are randomly oriented. A modest applied magnetic field can cause a larger degree of alignment of the magnetic moments with the external field, giving a large multiplication of the applied field.

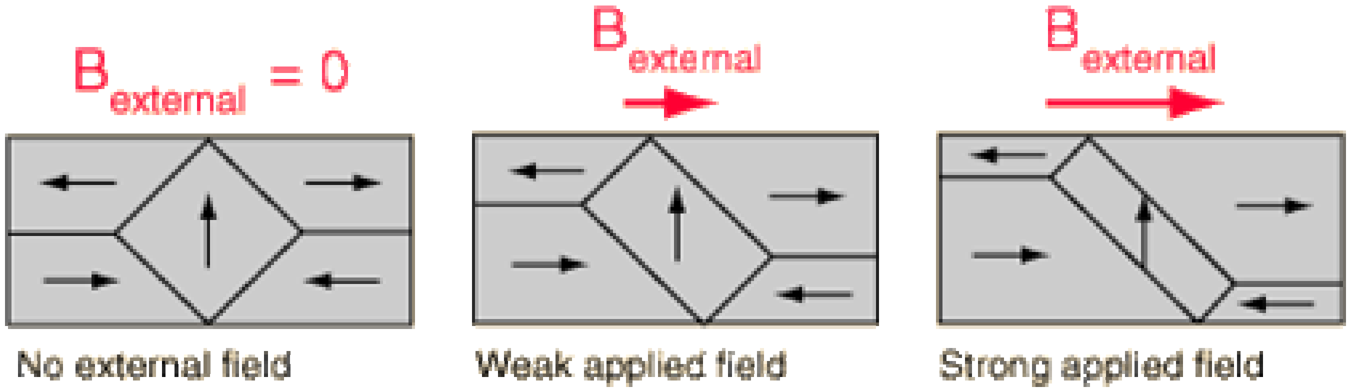
Internal magnetic fields (M) which come from the long range ordering of the electron spins are much stronger, sometimes hundreds of times stronger, than the external magnetic fields (H) required to produce these changes in domain alignment.

$$B = \mu H = \mu_r \mu_o H = \mu_o (1+\chi) H = \mu_o (M+H)$$

The effective multiplication of the external field which can be achieved by the alignment of the domains is often expressed in terms of the relative permeability. $\mu = (1+\chi)\mu_o = \mu_r \mu_o$, $B = \mu H$

Domains may be made visible with the use of magnetic colloidal suspensions which concentrate along the domain boundaries. The domain boundaries can be imaged by polarized light (because EM fields perpendicular to each other) , and also with the use of electron diffraction (domain arrangement?).

Single Crystal (Ni)

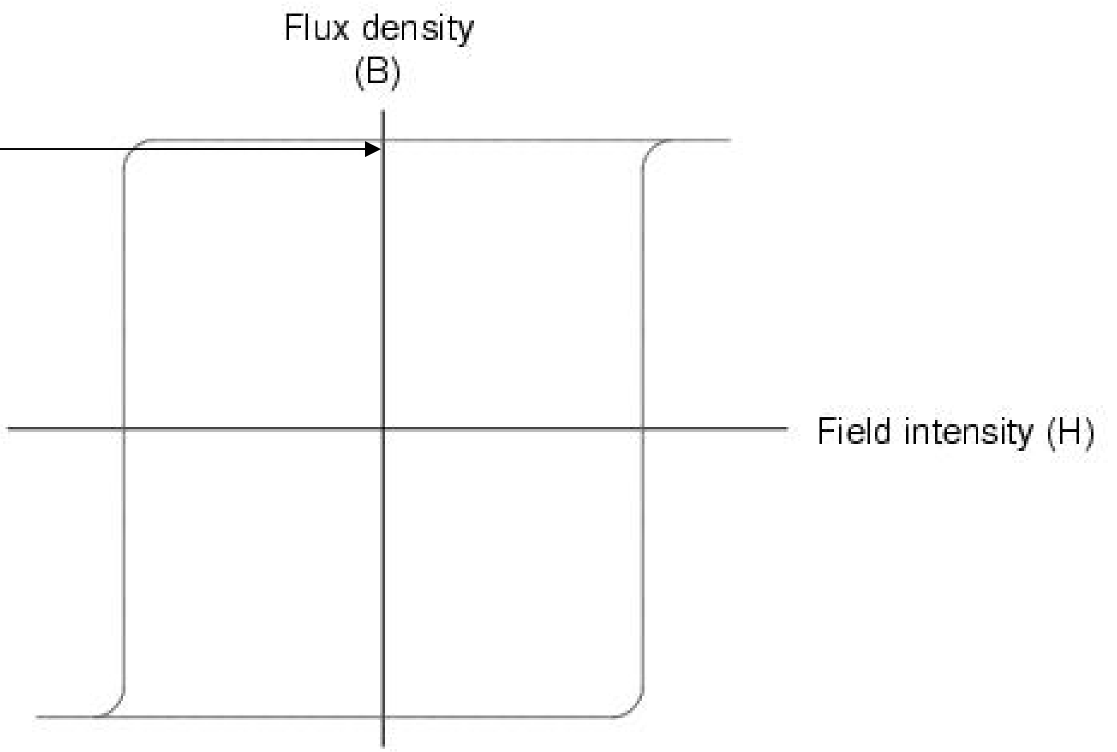


<u>the effect of external magnetic fields is to cause the domain boundaries to shift in favor of those domains which are parallel to the applied field</u>.

Applied to bulk magnetic materials which are polycrystalline causes the reorientation and also growth in dipole along the direction of applied magnetic field (external field large enough to realign dipoles not in the direction of dipole)

Ferromagnets will tend to stay magnetized to some extent after being subjected to an external magnetic field. This tendency to "remember their magnetic history" is called hysteresis. The fraction of the saturation magnetization which is retained when the driving field is removed is called the remanence of the material, and is an important factor in permanent magnets

Hysteresis curve for ferrite



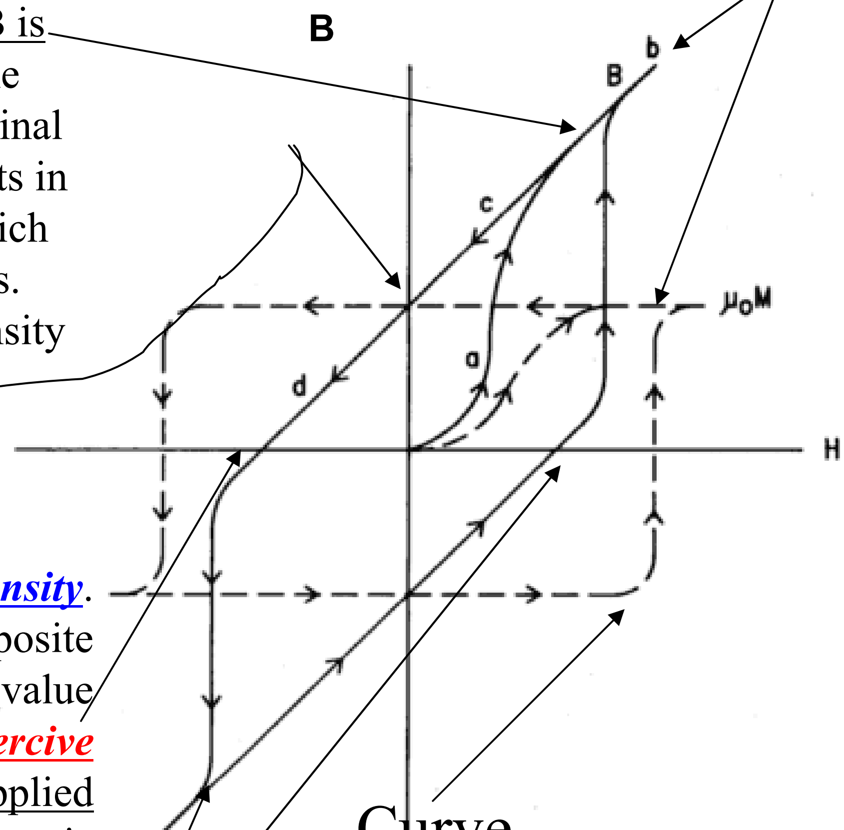
Starting from an unmagnetized magnet, as H is increased from zero, its effect is to align the atomic moments and give rise to a rapid increase in M. Thus the flux density B follows a path such as 'a' in figure. As all the atomic moments are aligned, M comes to its saturation value and any further increase in B is then due solely to the applied field alone (region b). As the applied field is reduced to zero, B does not follow its original path because of the 'lock-step' holding the atomic moments in the same direction. So the flux density follows path c, which includes a constant contribution from the atomic moments. This time as H (the external field) nears zero, the flux density nears a value due to the atomic moments alone

$$B_r = \mu_0\,(0+M_r)$$

residual

and the value of B at zero field is the *remanent* ***flux density***. Now as the direction of H is reversed, H and M act in opposite directions and the ***flux density*** is reduced (path d). The value of field at which B is reduced to zero is termed the ***coercive force*** of the magnet ${}_BH_C$. When the magnitude of the applied field is large enough to break the 'lock-step' the atomic moments fly around to align with the new field direction. The value of field at which this occurs is called the ***intrinsic coercive force*** of the permanent magnet ${}_MH_C$. So there are two different but related coercivities associated with a permanent magnet.

Saturated
Flux density



Curve
For ferrite
After atomic
moments are all
line up

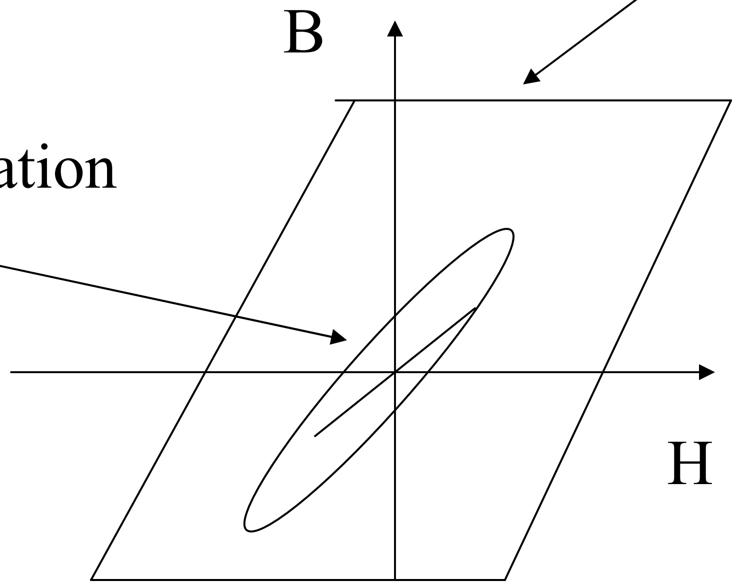
Before Saturation

BH curve after saturation

$B = \mu_r \mu_o (M+H)$

BH curve before saturation

$B = \mu_r \mu_o H$

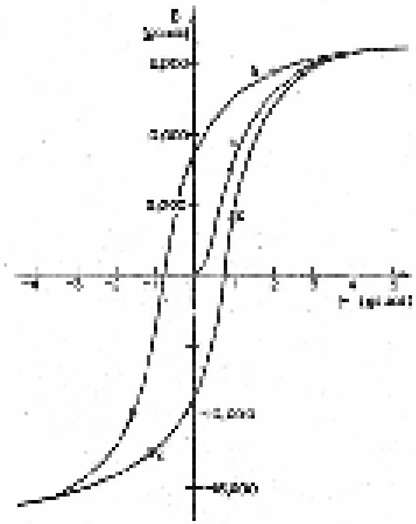


Magnetic Properties of Ferromagnetic Materials

Material	Treatment	Initial Relative Permeability	Maximum Relative Permeability	Coercive Force	Remanent Flux Density
Iron, 99.8% pure	Annealed	150	5000	1.0	13,000
Iron, 99.95% pure	Annealed in hydrogen	10,000	200,000	0.05	13,000
78 Permalloy	Annealed, quenched	8,000	100,000	.05	7,000
Superpermalloy	Annealed in hydrogen, controlled cooling	100,000	1,000,000	0.002	7,000
Cobalt, 99% pure	Annealed	70	250	10	5,000
Nickel, 99% pure	Annealed	110	600	0.7	4,000
Steel, 0.9% C	Quenched	50	100	70	10,300
Steel, 30% Co	Quenched	...	...	240	9,500
Alnico 5	Cooled in magnetic field	4	...	575	12,500
Silmanal	Baked	...	...	6,000	550
Iron, fine powder	Pressed	...	...	470	6,000

B-H Loop for Soft and Hard Magnetic Materials

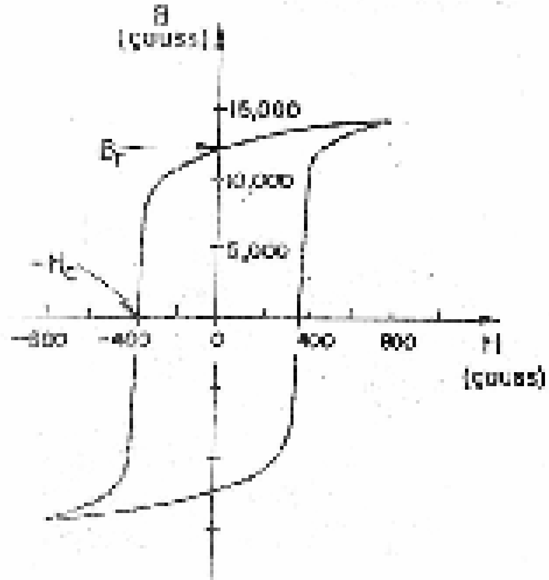
soft



Soft Iron

- Narrow B-H loop
- Large magnetization change from s very small applied field
- Useful for transformers and motors

hard



Alnico V alloy

- 51% Fe, 8% Al, 14% Ni, 24% Co, 3% Cu
- Composition very critical
- Wide B-H loop (500x larger than soft iron)
- Good permanent magnet

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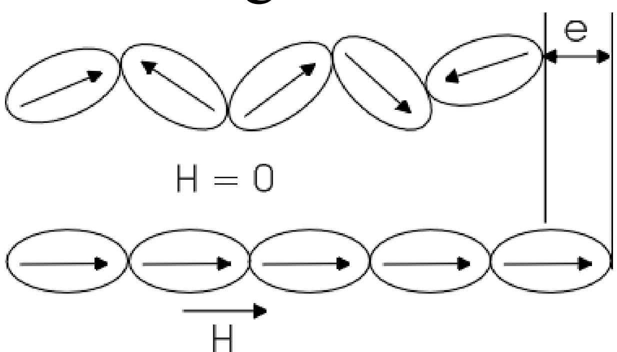
Magnetostriction Effect

Magnetostriction is the changing of a <u>material's physical dimensions in response to changing its magnetization</u>.

On a Macroscopic level may be segregated into two distinct processes:

The first process is dominated by the <u>migration of domain</u> walls within the material in response to external magnetic fields. Second, is the <u>rotation of the domains</u>.

These two mechanisms allow the material to change the domain orientation which in turn causes a dimensional change.



Magnetic sensor and actuator

Ampere's law

$B * L = \mu_o i$

Faraday's law of induction

$V = -N d\phi_B / dt = L \, di/dt$

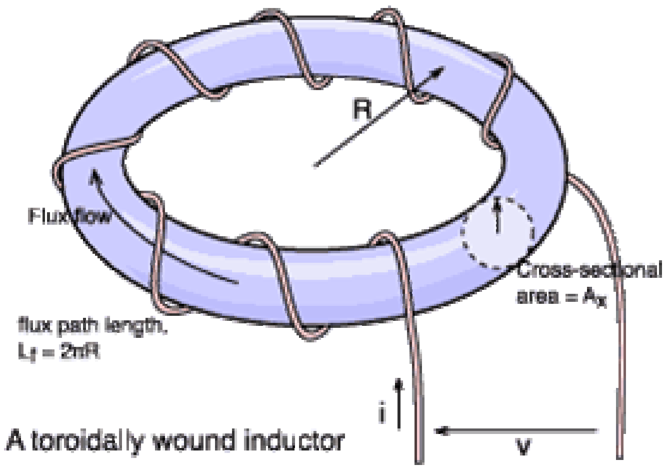
Magnetic force

$F = il \times B$

magnetic actuators

- Coil gun
- Solenoids
- Relay (mechanical switch)
- Actuator for cantilever structure
  - Electromagnetic Coil actuator
  - Permalloy magnetic actuator
- Levitation

Electromechancial Relay



One method of calculating the force produced by a magnetic field involves an understanding of the way in which the energy represented by the field changes. To derive an expression for the field energy we'll look at the behaviour of the field within a simple toroidal inductor. We equate the field energy to the electrical energy needed to establish the coil current.

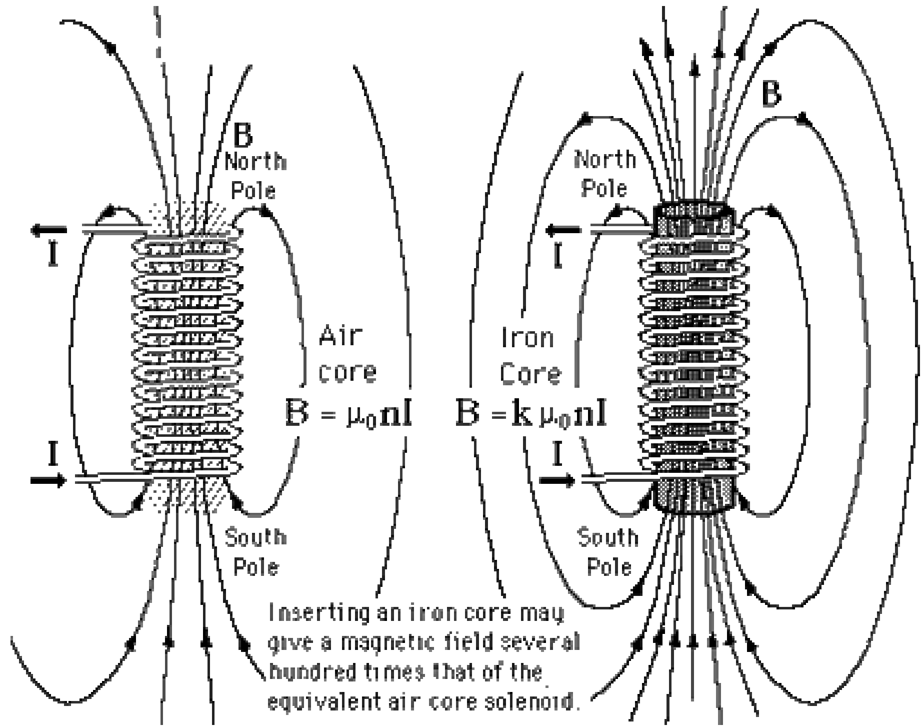
When the coil current increases so does the magnetic field strength, H. That, in turn, leads to an increase in magnetic flux, Φ. The increase in flux induces a voltage in the coil. It's the power needed to push the current into the coil against this voltage which we now calculate.

We choose a toroid because over its cross-sectional area, A, the flux density should be approximately uniform (particularly if the core radius is large compared with it's cross section). We let the flux path length around the core be equal to L_f and the cross-sectional area be equal to A_x. We assume that the core is initially unmagnetized and that the electrical energy (W) supplied to the coil will all be converted to magnetic field energy in the core (we ignore eddy currents).

$$W = \int_0^t v \times i \, dt \quad \text{joules}$$

Iron Core Solenoid

An iron core has the effect of multiplying greatly the magnetic field of a solenoid compared to the air core solenoid on the left.



Faraday's law gives the voltage as

$$v = N \times d\Phi/dt \quad \text{volts}$$

Energy calculation of Coil to the core

Substituting:

$$W = \int_0^t N(d\Phi/dt)i\,dt$$

$$W = \int_0^\Phi N \times i\,d\Phi$$

Now, $N\times i = F_m$ and $H = F_m/L_f$ so $N\times i = H\times L_f$. Substituting:

$$W = \int_0^\Phi H\times L_f\,d\Phi$$

Also, from the definition of flux density $\Phi = A_x \times B$ so $d\Phi = A_x \times dB$. Substituting:

$$W = \int_0^B H\times L_f \times A_x\,dB \quad \text{joules}$$

This gives the total energy in the core. If we wish to find the *energy density* then we divide by the volume of the core material:

$$W_d = \left(\int_0^B H\times L_f\times A_x\,dB\right)/(L_f\times A_x)$$

$$W_d = \int_0^B H\,dB \quad \text{joules m}^{-3}$$

If the magnetization curve is linear (that is we pretend B against H is a straight line, not a curve) then there is a further simplification. Substituting $H = B/\mu$

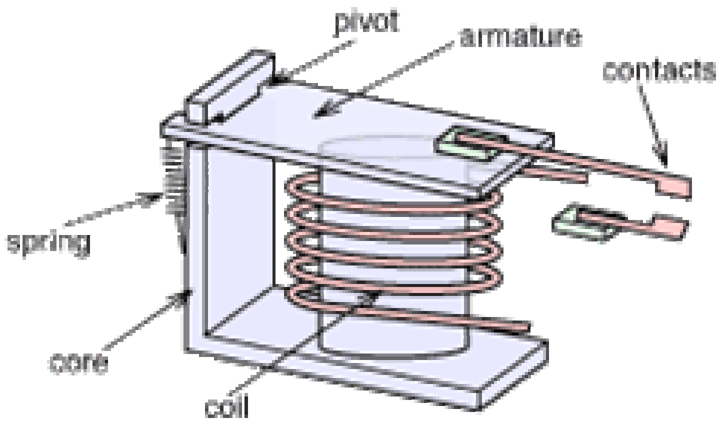
$$W_d = \int_0^B B/\mu\,dB$$

$$W_d = B^2/(2\mu) \quad \text{joules m}^{-3}$$

Compare this result with the better known formula for the energy stored by a given inductance, L: $W_L = L\times I^2/2$ joules

$L = N \times \Phi / I$

Some problems of practical importance can be solved when the air gap between the electromagnet and the work piece is small in comparison with the field cross section. This is the situation found in most electromechanical relays.



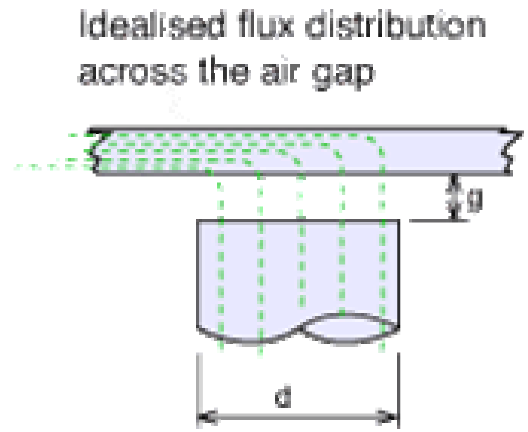


Fig. FRR An electromechanical relay

gives the energy density (joules per metre cubed). Assuming that the field inside the air gap is uniform you can use EFB to get the total field energy simply by multiplying by the volume of the field, V

$$W_d = B^2/(2\mu) \text{ joules m}^{-3}$$

$$V = g \times A$$

where g is the gap length and A is the cross sectional area of the coil's core. The total energy is then

$$W = (B^2/(2\mu_0)) \times (g \times A)$$

We need the force on the armature. That is given by the rate of change of energy with gap length

$F = dW/dg$

$$\boxed{F = B^2 A / (2\mu_0)}$$

We next need to find the flux density, B. It's assumption time again. Well designed relays use such high permeability material for the core and armature that most of the field strength produced by the coil will appear across the air gap between the core and the armature and we can ignore the reluctance of the core, pivot and armature. Substituting equation TMH into equation TMD we get

$B = \mu \times H$

$B = F_m \mu_0 / g$

$H = F_m / l_e$

Substituting into Equation FRP

$$\boxed{F = (F_m)^2 \mu_0 A / (2 g^2)}$$

magneticmotive force

$F_m = Ni$

$$\boxed{F = (Ni)^2 \mu_o A / (2g^2)}$$

Example

If you have ever tried to bring a piece of iron into contact with a magnet manually then you will quite literally have a feel for the g^2 term!

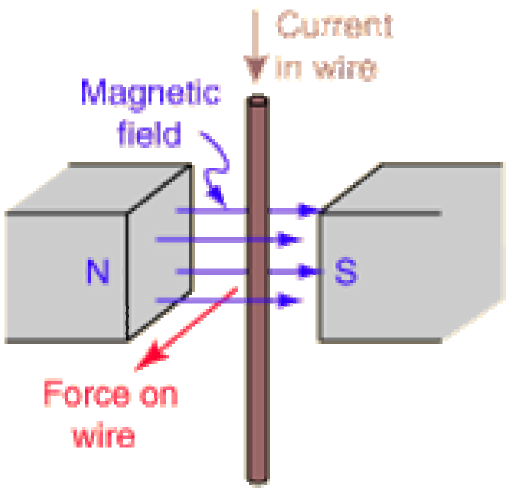
Example: A relay has a coil of 1200 turns. The diameter of the coil core is 6 millimetres and the air gap is 1.8 millimetres. The spring exerts a force on the armature of 0.15 newtons at the part of it opposite the air gap. What coil current will operate the relay?

The core cross sectional area, $A = \pi\,(0.006/2)^2 = 2.83\times10^{-5}\ \mathrm{m}^2$. Substituting into equation FRS

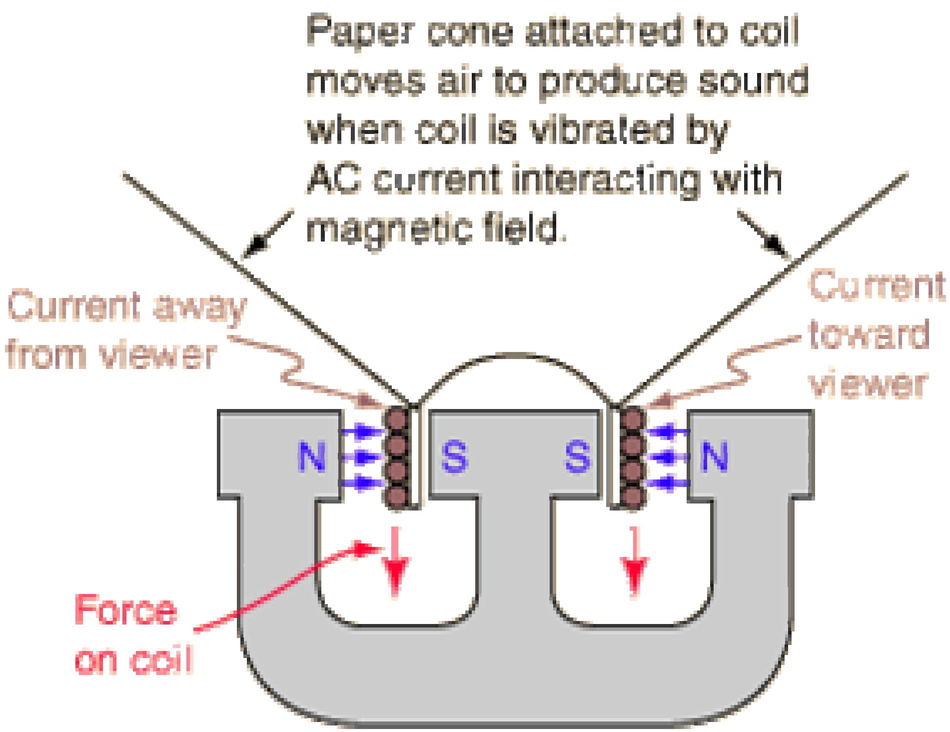
$$0.15 = (1200 \times I)^2\ 4\pi\times10^{-7} \times 2.83\times10^{-5} / (2 \times (1.8\times10^{-3})^2)$$

Therefore I = 0.138 amps. The flux density will be 0.116 teslas. This should be well below saturation for iron. As the gap closes, and g goes to zero, equation FRS predicts that the force on the armature becomes infinite. Of course it won't do so because our assumptions about the field production will go down the tubes first. Under those conditions it might be far harder to calculate the force precisely. One point to note, though, is that flux density is limited by saturation to below about 1.6 teslas. Equation FRP therefore sets a limit on the force of one million newtons per square metre (about 100 tons).

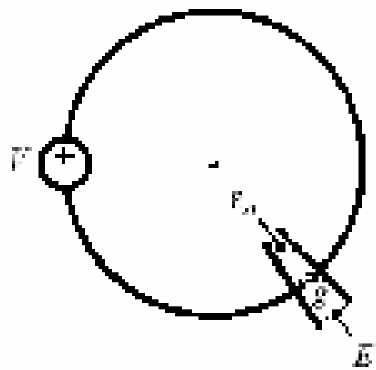
Dynamic loudspeaker principle



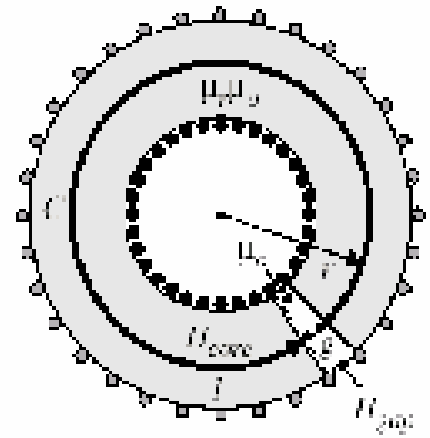
A current-carrying wire in a magnetic field experiences a magnetic force perpendicular to the wire.



Comparison of Electrical and Magnetic Energy Density



(a)



(b)

$$W_e = \frac{\varepsilon A V^2}{2g} \qquad W_m = \frac{\mu_0 A n^2 I^2}{2g} \qquad W_m = \frac{A M_s^2 (g+l)}{2\;{}_0}$$

$$F_e = \frac{\varepsilon A V^2}{2g^2} \qquad F_m = \frac{\mu_0 A n^2 I^2}{2g^2} \qquad F_m = \frac{A M_s^2}{2\;{}_0}$$

Unsaturated System | **Magnetization Saturated**

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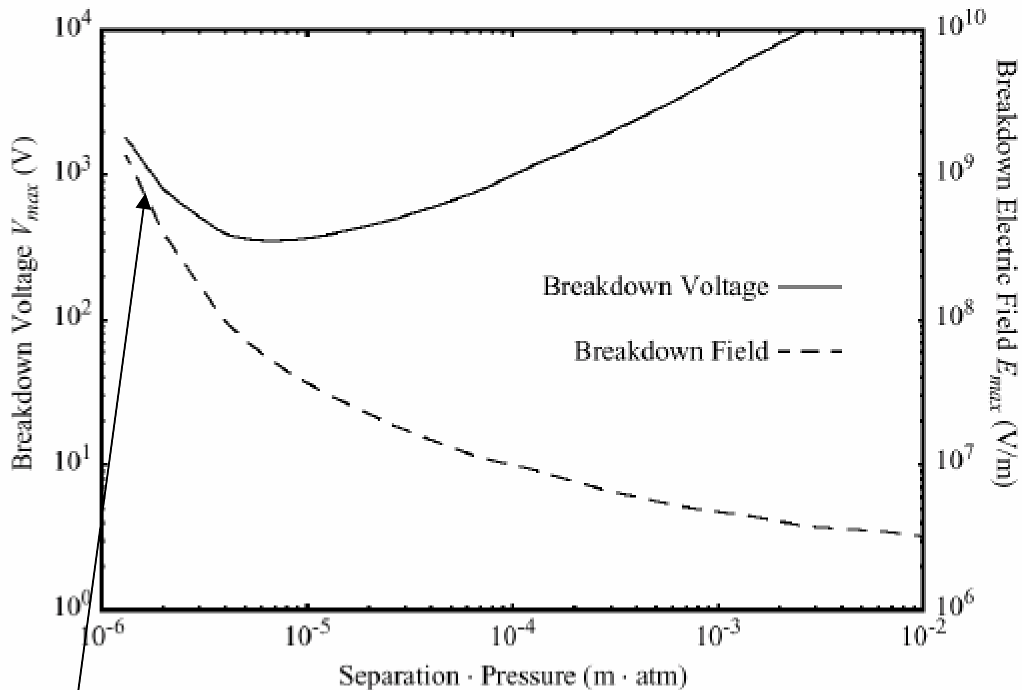
m.c. wu

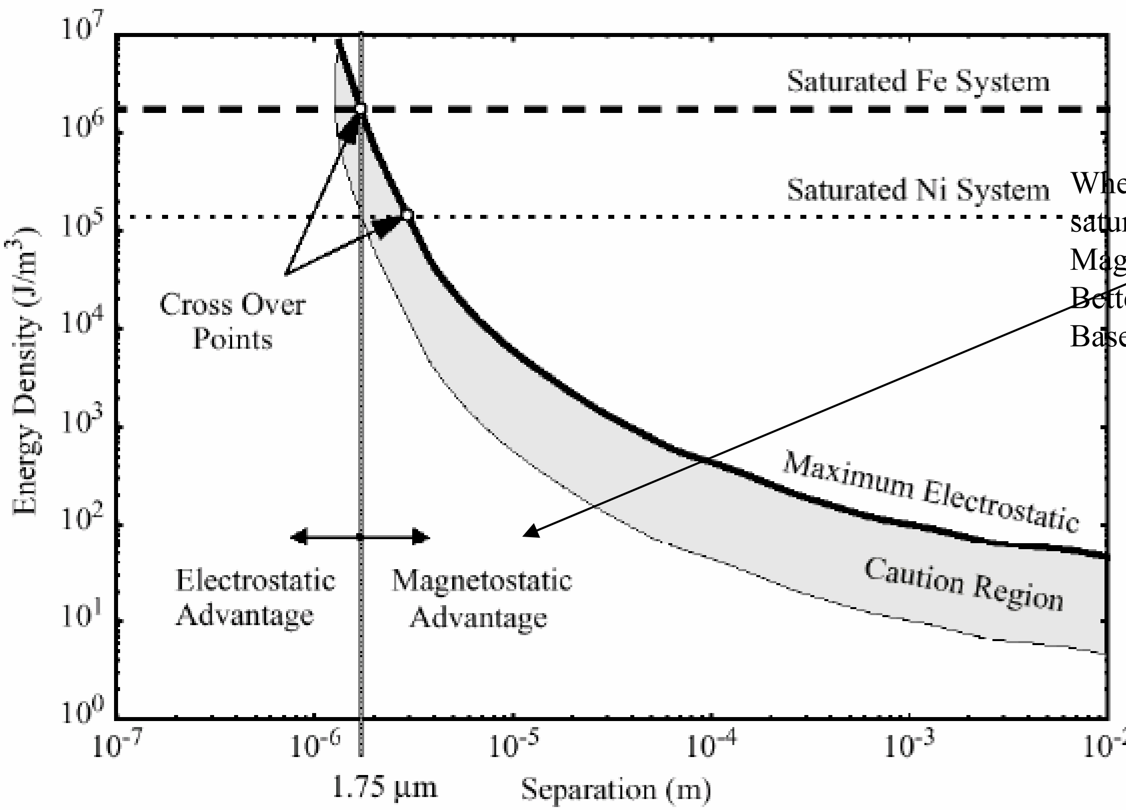
Coil based permalloy

Paschen's Curve



- Maximum voltage (field) that can be applied before breakdown
- Breakdown field increases at small scale because there are too few impacts of ionized molecules for regenerative avalanche breakdown
- For every pressure, there is a gap separation where the breakdown voltage is minimum

Scaling of Elecstrostatic and Magnetostatic Energy Densities



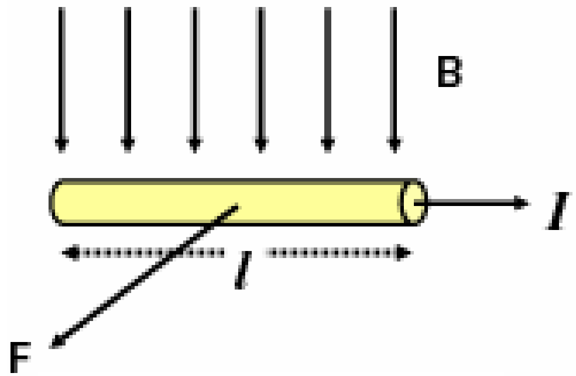
When ferromagentic materials saturated, it acts like permanent Magent so magentic becomes Better choice. This is a curve Based on1.75um separation

Figure 3-7 Maximum energy densities for electrostatic and magnetostatic systems (Ni and Fe) in air at a pressure of 1 atm.

J. Judy, Ph.D. Thesis

Lorentz Force

Coil based actuator



$$\vec{F} = I(\vec{l} \times \vec{B})$$

- Simple to fabricate, commonly used
  - Does not require deposition of magnetized thin films, which is usually difficult to control
- Relatively large force
  - For length = 1 mm, I = 10 mA, B = 1 Tesla
    $F = 10^{-6}$ N
  - Force can be increased with multiple turns of current filament
- Resistance of the conductor must be minimized to reduce power consumption

m.c. wu

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Faraday's Law of Induction

Electromotive Force (EMF) $$\int_{CP} E \cdot ds = -\int_S \frac{\partial B}{\partial t} \cdot dA = -\frac{\partial \Phi_B}{\partial t}$$

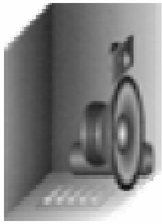
CP: Closed Path
Φ_B: Magnetic flux

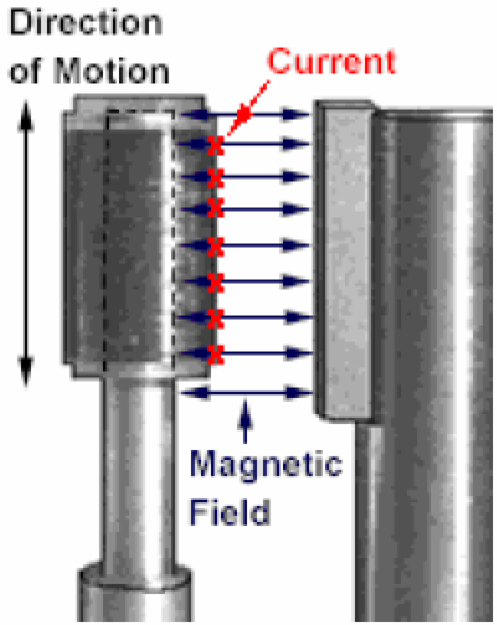
$$V = N\frac{\partial(BA)}{\partial t} = NB\frac{\partial(Lx)}{\partial t} = NBL\frac{\partial x}{\partial t}$$

L: Area of coil exposed to magnetic field
N: Number of turns
x: Height of coil
dx/dt: Velocity of coil movement

Voltage across the coil is proportional to its velocity

Voice Coil

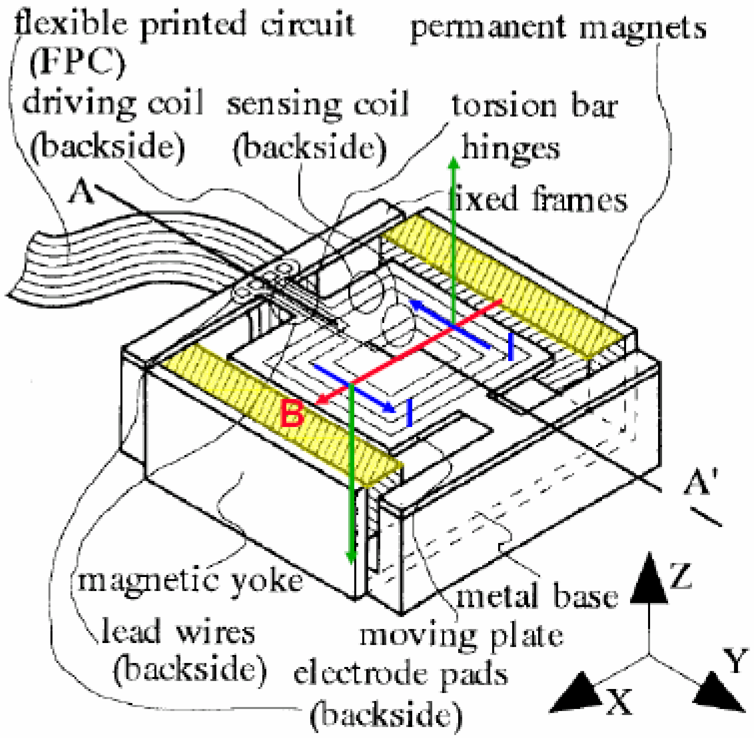




http://bits.me.berkeley.edu/beam/vc_2.html

- Used in audio speakers, CD-ROM pickup head, computer disk drives
- Force (and direction) proportional to the current
- Voltage proportional to the velocity
- Advantages:
  - Low driving voltage
  - High force-to-mass ratio
  - Linear constants
  - Cog-free and hysteresis-free motion
- Issue:
  - Heat, power consumption

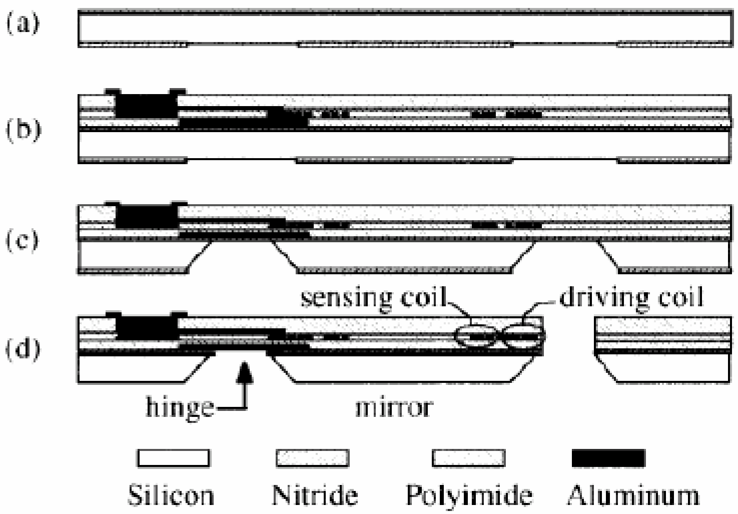
Electromagnetically Actuated Optical Scanner



- **Drive current:**
  - **± 20 mA sinusoidal**
- **Mirror area ~ 20 mm²**
- **Scanners demonstrated:**
  - **Fast scanner:**
    1° range at 1.7 kHz
  - **Slow scanner:**
    60° range at 72 Hz

H. Miyajima, et al., Transducers 1999.

Torque and Sensing Voltage



Torque

$$T = I \cdot B \cdot l_1 \cdot l_2 \cdot n$$

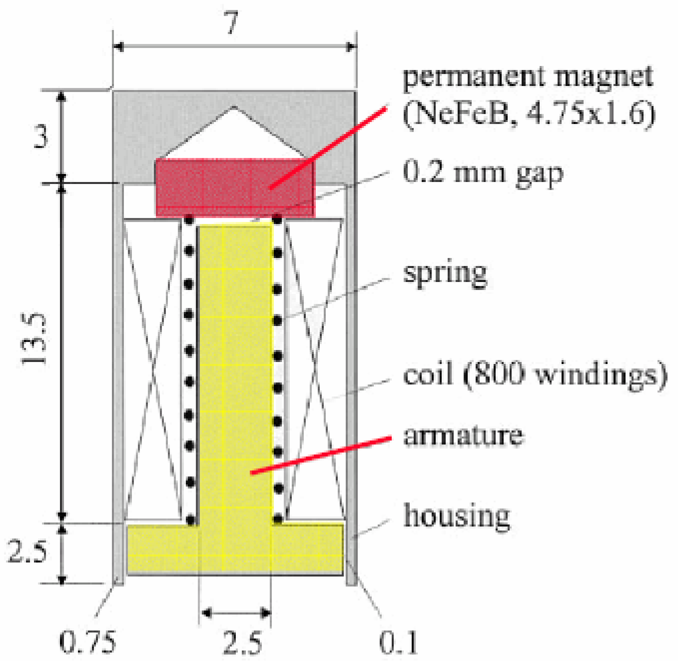
Number of turns
Coil spacing
Coil length
Magnetic flux density
Current

Sensing Coil Voltage

$$V = v_s B_s l_{s1} n_s = \dot{\theta}_m B_s l_{s1} l_{s2} n_s$$

Sensing coil spacing
Sensing coil length
Velocity

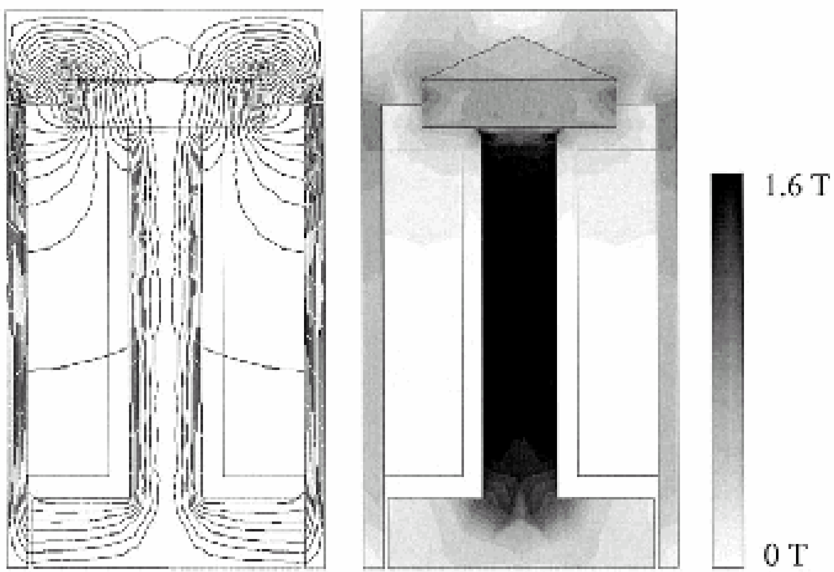
Examples of Electromagnetic Actuator



S. Bohm, et al., "A micromachined silicon valve driven by a miniature bi-stable electro-magnetic actuator," Sensors and Actuators, vo. 80, p. 77-83, 2000

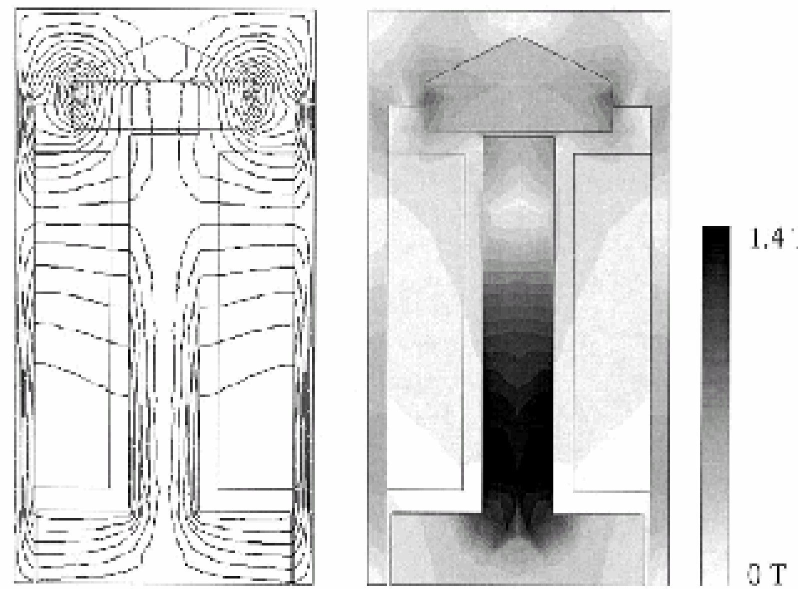
- Bistable electromagnetic actuator
  - Used in relays, latches for read-write head in harddisk drives, valves
- Bistable
  - Current pulse required to switch state
  - No power consumption except during switching
- Material parameters:
  - Soft iron (armature and housing)
    - Relative permeability $\mu_r = 5000$, saturation at 1.5 T
  - Permanent magnet (NeFeB)
    - Coercive field $H_c = 8.3 \times 10^5$ A/m
    - $B_r = 1.14$ T
  - Coil
    - 800 windings

Magnetic Flux Distri
(1) Closed Position



Peak flux density = 1.56 T
Attractive force between armature and magnet = 2.15 N

Magnetic Flux Distriubti
(2) Open Position



Negative current is sent through coil

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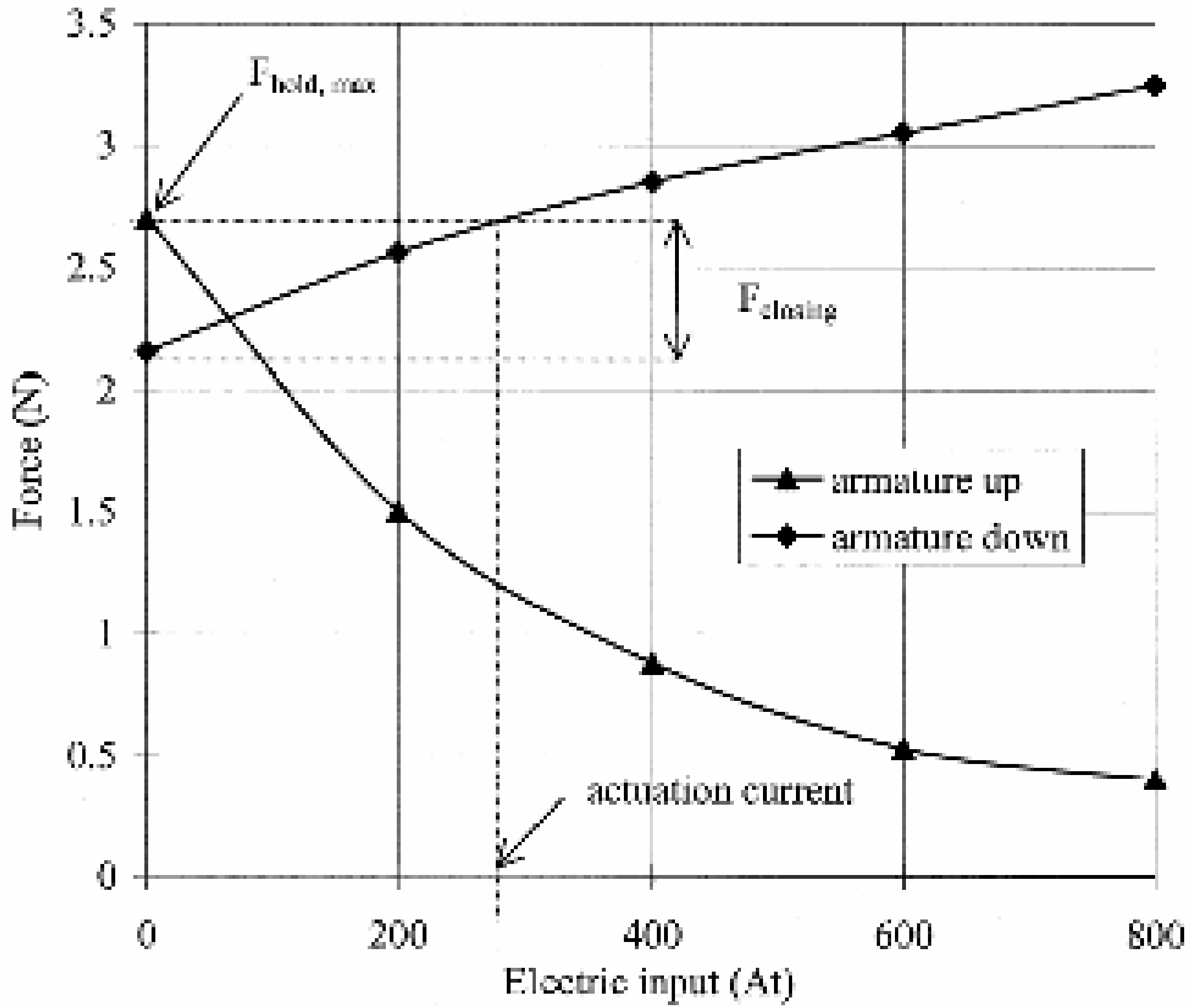
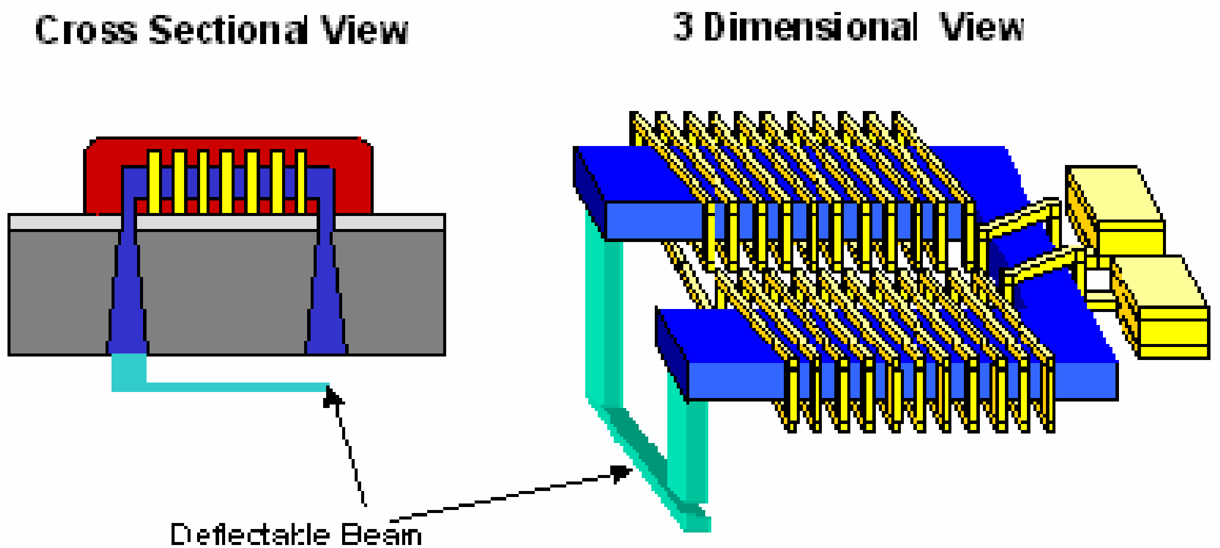
Calculated Force versus Current

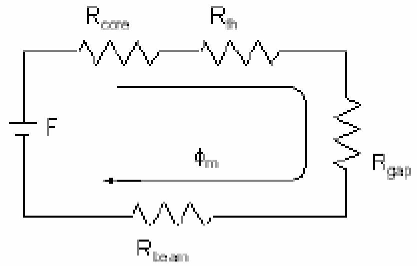


Design - Test Structure Consisting of Actuator and Cantilever Beam



Magnetic Circuit Analysis

- Equivalent Circuit



F = Magnetomotive Force (NI)
ϕ_m = Magnetic Flux
R = Reluctance

Magnetic Circuit Analysis

- Reluctance Equations

$$R_{core} = \frac{l_{core}}{\mu_0 \cdot \mu_r \cdot t_{core} \cdot w_{core}} \qquad R_{th} = \frac{l_{th}}{\mu_0 \cdot \mu_r \cdot A_{th}}$$

$$R_{beam} = \frac{l_{beam}}{\mu_0 \cdot \mu_r \cdot t_{beam} \cdot w_{beam}} \qquad R_{gap} = \frac{(g-x)}{\mu_0 \cdot A_{gap}}$$

- Energy and Force Equations

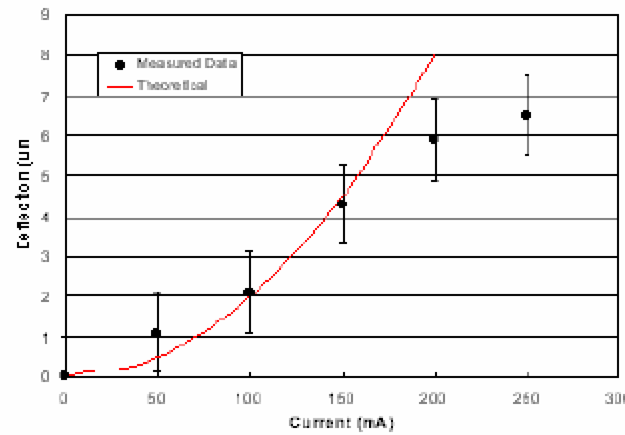
$$W_m = \frac{1}{2}\frac{(NI)^2}{(R_{core}+R_{th}+R_{gap}+R_{beam})}$$

$$F_t = \frac{\partial W_m}{\partial x} = \frac{1}{2}\frac{(NI)^2}{\mu_0 A_{gap}(R_{core}+R_{th}+R_{gap}+R_{beam})^2}$$

Testing and Results

- Electrical Parameters at Low Frequency (<1kHz)
  - Inductance: 3.5 μH
  - Resistance: 1.4 - 2.1 Ω
- Cantilever Deflection
  - Applied current: 50 - 250 mA
  - Measured deflection with high power microscope
  - Max deflection: 6.5 μm

Deflection vs. Actuator Current



Permalloys
– Very Soft Magnetic Materials

- Very easy to magnetize
  - Need pure, well-annealed materials with very few dislocations and impurities so the magnetic domain walls move easily
- Small anisotropy
  - Fe prefers to magnetize along [100]
    Ni prefers to magnetize along [111]
  - Right mixture of Ni and Fe wouldn't prefer any direction
  - Right mixture ~ 70% Ni + 30% Fe
- Useful for high quality transformers
- Needs to be handled carefully (low stress, no bending, ..)

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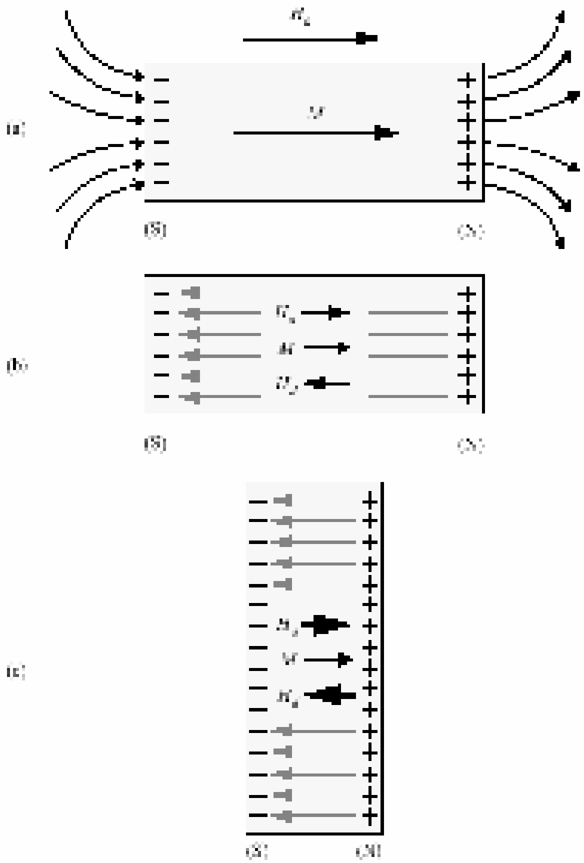
Shape Anisotropy



Since permalloy has very small material anisotropy (due to crystals, stress, ..), asymmetry in shape can induce significant magnetic anisotropy

The internal demagnetization field along a short axis is larger (c) than that along a long axis (b).

It is easier to magnetize the sample along the long axis
Easy axis

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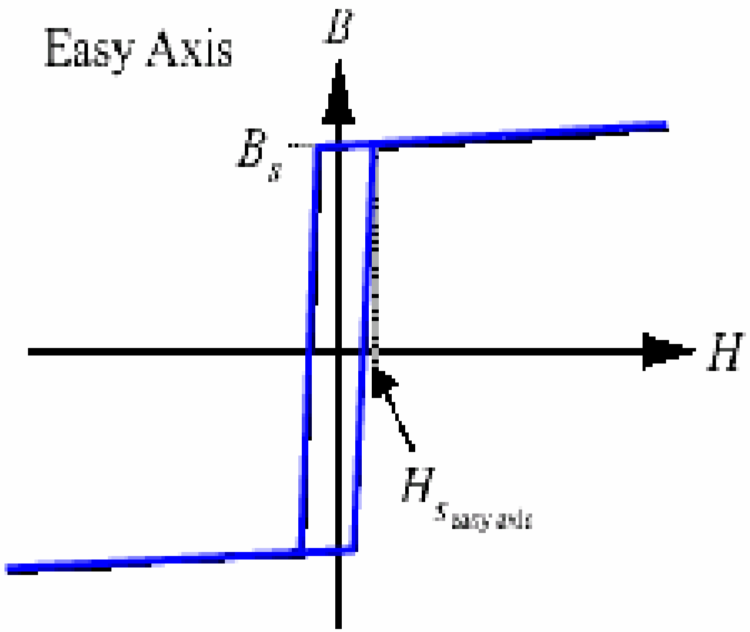
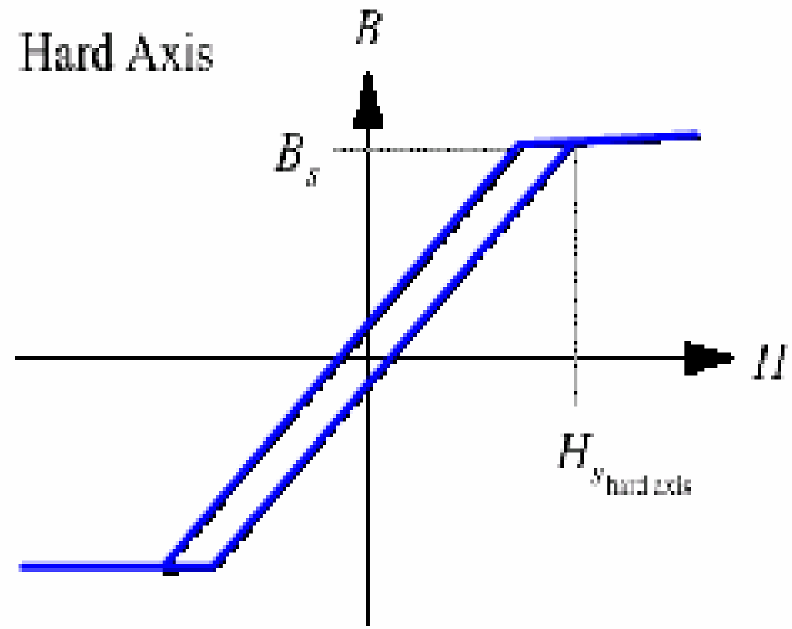
Easy Axis and Hard Axis



(a)



(h)

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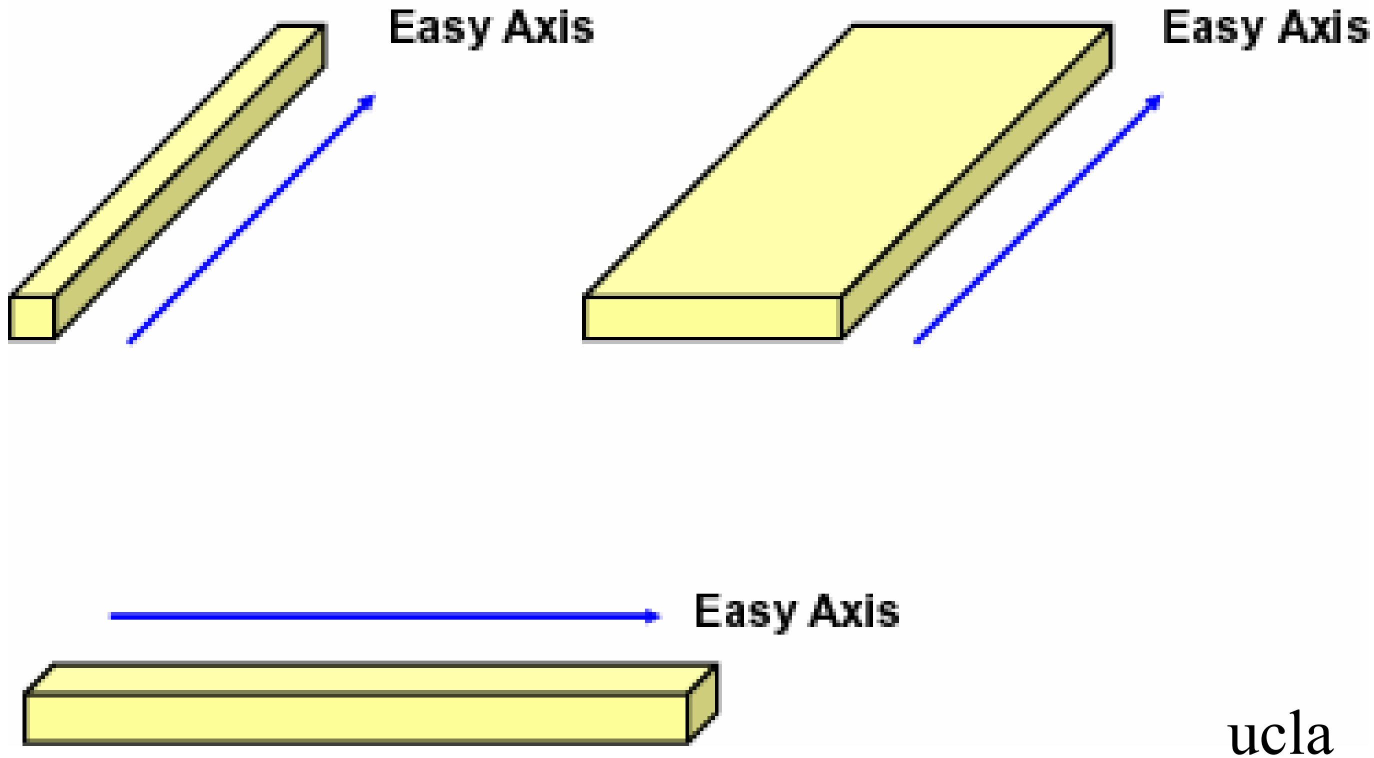
Shape Anisotropy

Easy axis aligns with the longest axis of the sample



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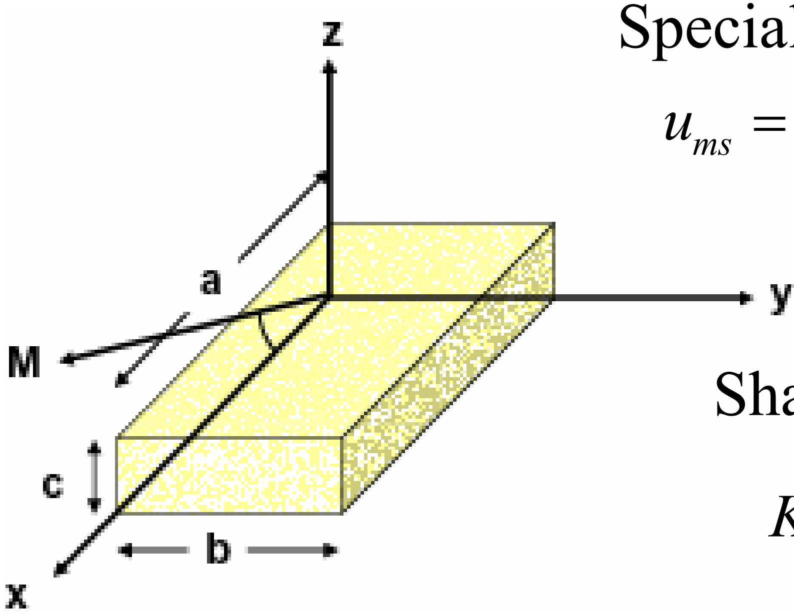
Magnetic Shape- anisotropy energy

Anisotropy energy $$u_{ms} = -\frac{1}{2}\vec{H}\cdot\vec{M}$$



Special case when M stays in c-z plane:

$$u_{ms} = \frac{1}{2\mu_o}(N_c - N_a)M_s^2\sin^2\theta = K_a\sin^2\theta$$

Shape anisotropy constant:

$$K_a = \frac{1}{2\mu_o}(N_c - N_a)M_s^2$$

N_a, N_b and N_c are shape coefficients

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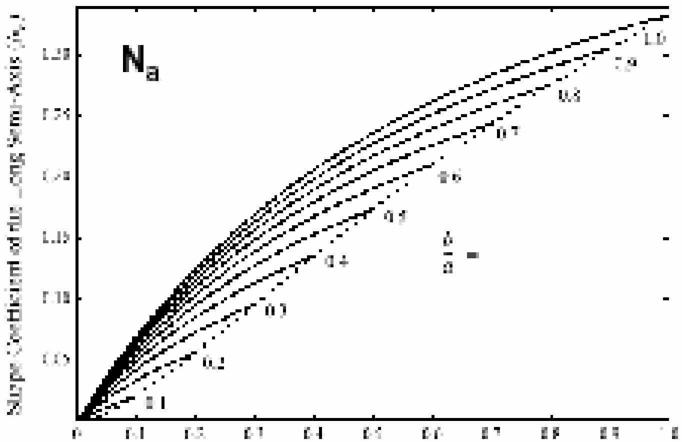
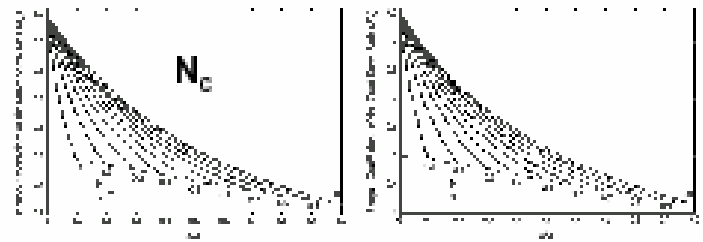
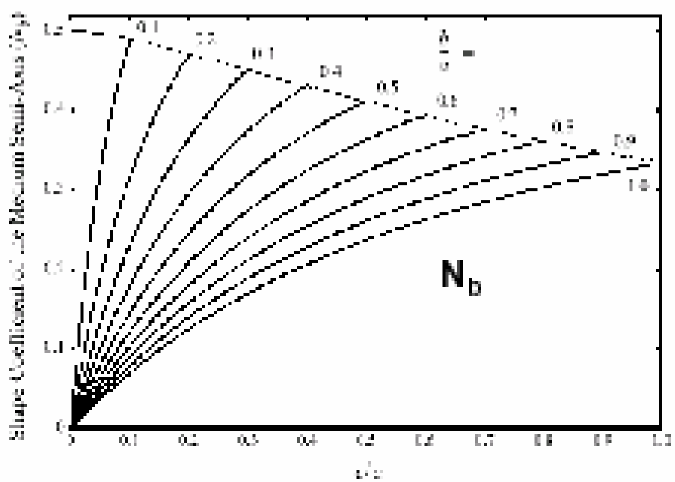
Shape Coefficients





c/a



N_a, N_b, N_c depends on shape parameters a, b, c (convention: a   b   c)

For example, a = 50 um, b = c = 5 um
b/a = 0.1, c/a = 0.1
N_a = 0.02, N_b = 0.48, N_c = 0.48

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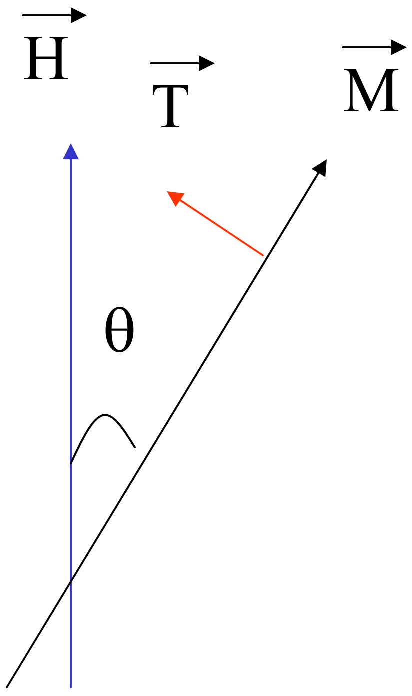
Magnetostatic Energy



Consider a magnetic material with magnetization M and volume V in a Magnetic field H, the maentostatic Energy is

$$U_{ms} = -V\vec{H}\cdot\vec{M}$$

Torque

$$\vec{T} = -\frac{\partial U_{ms}}{\partial\theta} = V\vec{H}\times\vec{M}$$

Note the torque is proportional to Volume (volume force)

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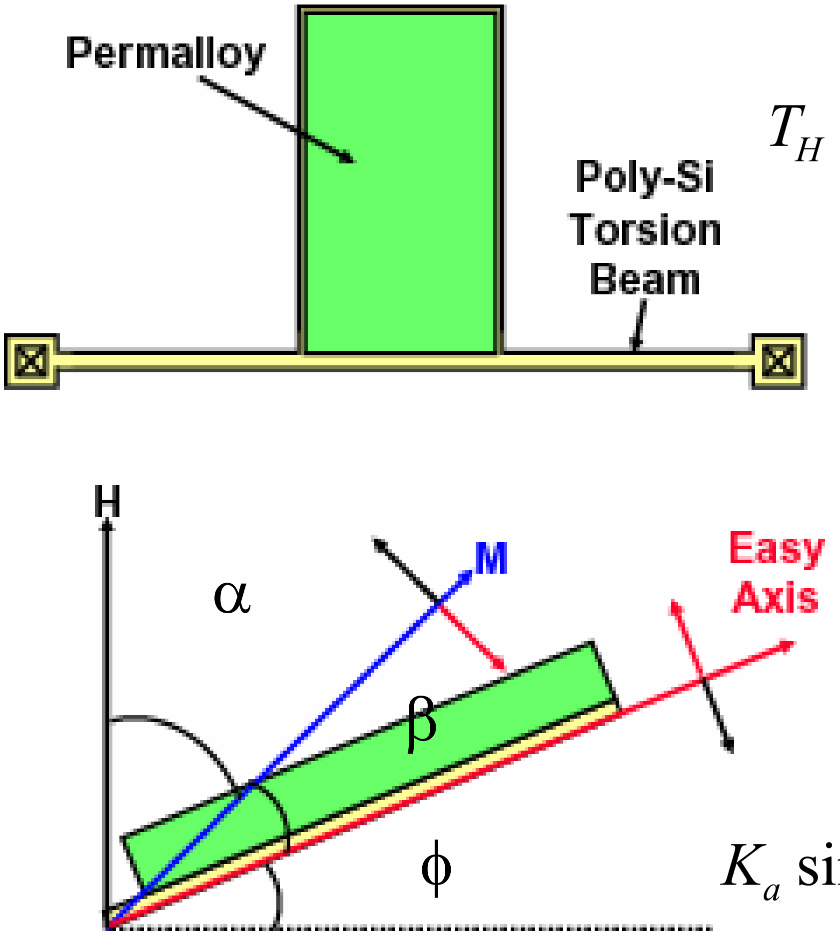
Permalloy plate in Magnetic Field



$$\vec{T}_H = V\vec{H} \times \vec{M}$$

$$T_H = VHM \sin\alpha = VHM \sin(\alpha - \beta - \phi)$$

$$T_{aniso} = -VK_a \sin(2\theta)$$

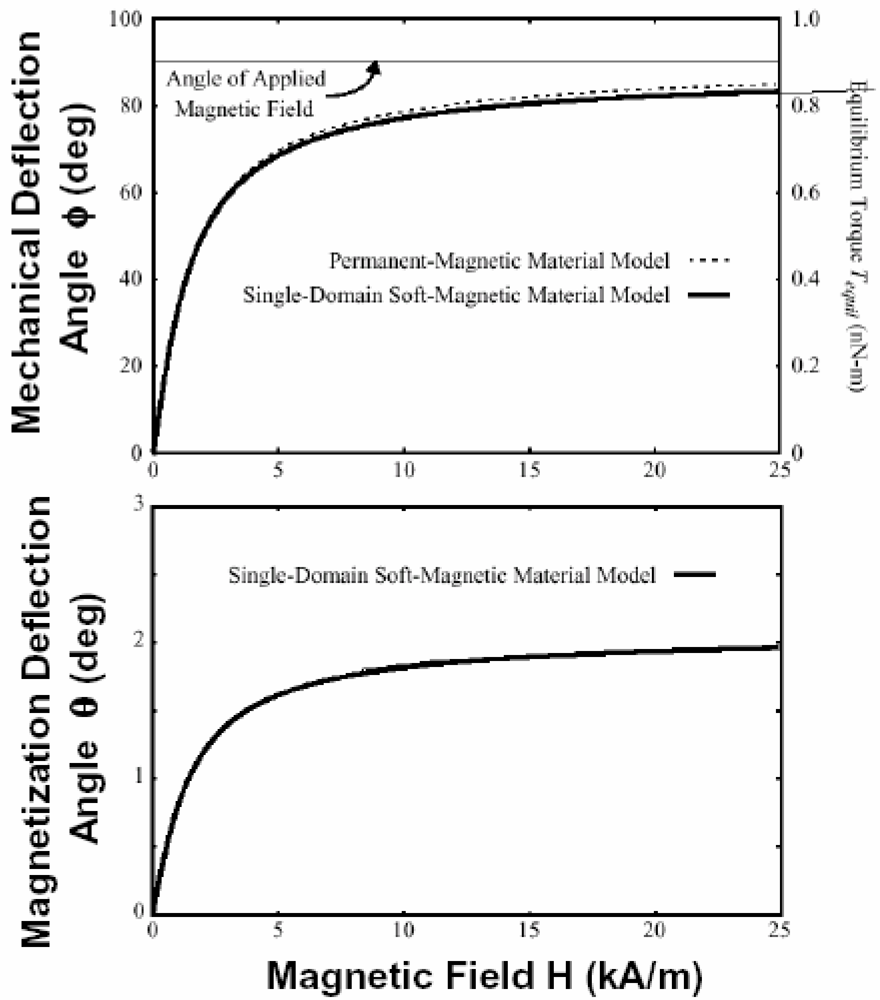
$$T_{mech} = -k_\phi \phi$$

At equilibrium:

$$\begin{cases} T_H + T_{aniso} = 0 \\ -T_{aniso} + T_{mech} = 0 \end{cases}$$

$$K_a \sin(2\theta) = HM \sin(\gamma - \theta - \frac{VK_a}{k_\phi}\sin(2\theta))$$

Transfer Characteristics



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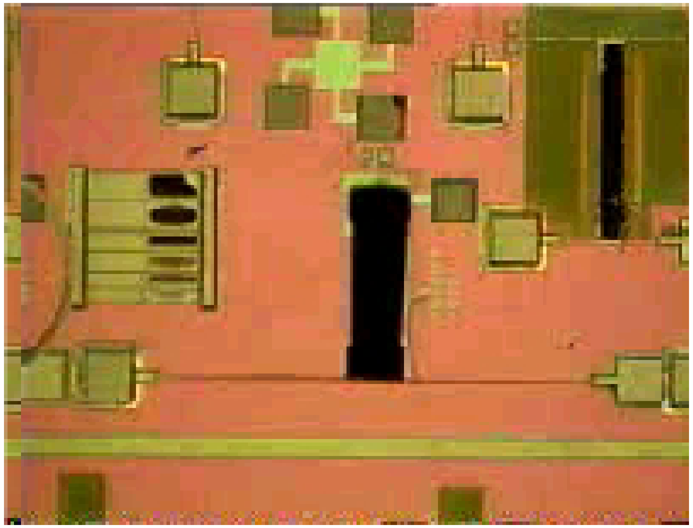
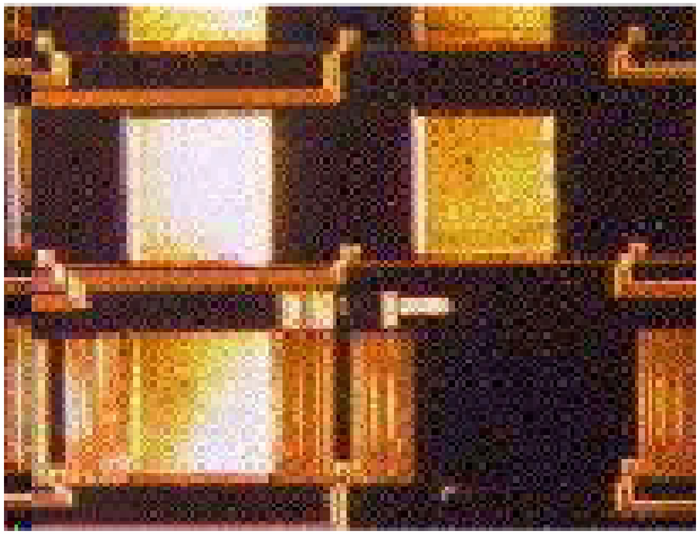
Magnetic Actuators in Motion (1)

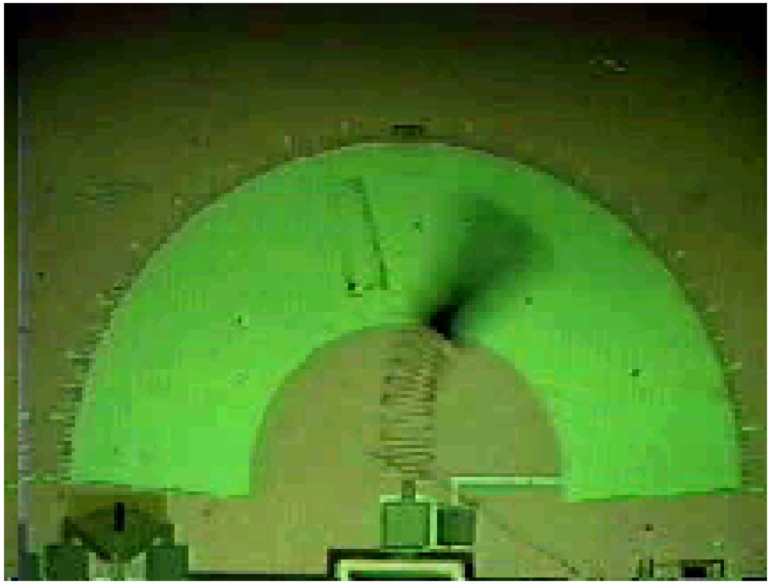


Magnetically Actuated Torsion Plate
(Courtesy Prof. J. Judy)

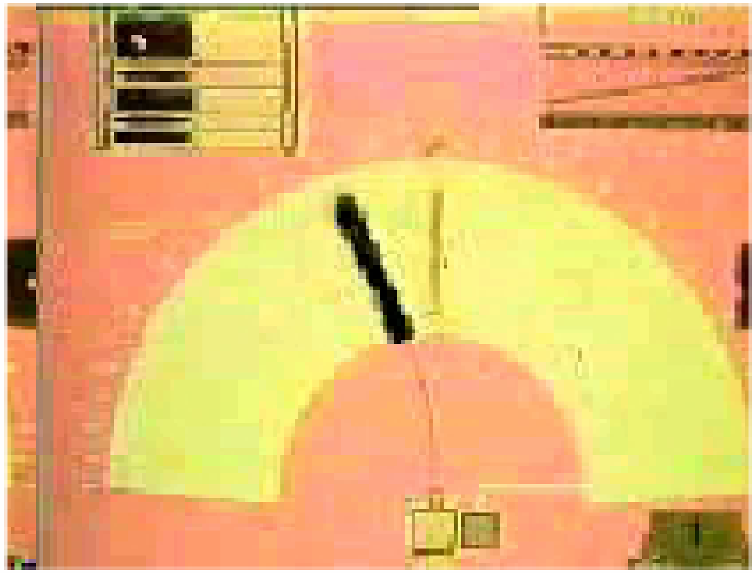


Magnetic Actuator with
Electrostatic Clamp
(Courtesy Prof. J. Judy)

Magnetic Actuators in Motion (2)

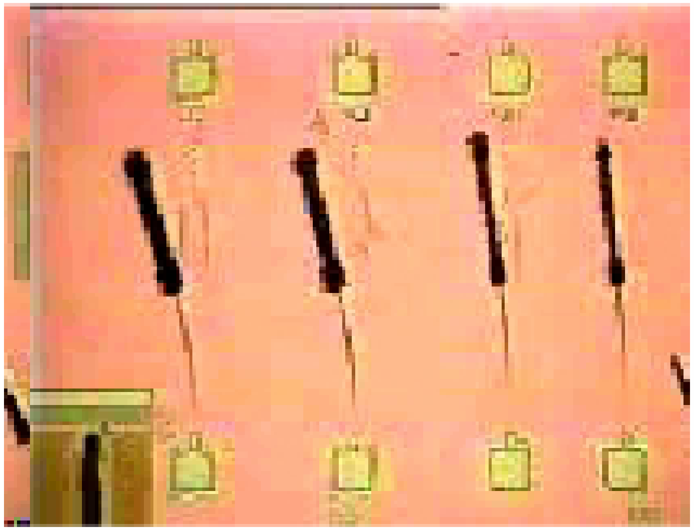


Magnetic Actuator in Liquid
(Courtesy Prof. J. Judy)

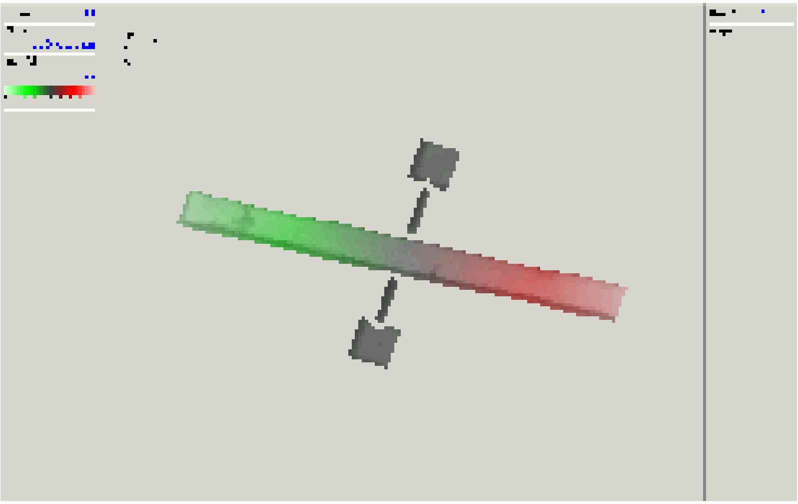


Large Deflections
(Courtesy Prof. J. Judy)

Magnetic Actuators in Motion (3)



Multiple Magnetic Actuators
(Courtesy Prof. J. Judy)



Magnetometer Motion Measured by LDV
(Courtesy Prof. J. Judy)

Magnetic levitation

- There are several methods to obtain magnetic levitation. The primary ones used in maglev trains are : EMS, EDS and Indutrack.
- **(Mechanically-stabilized Levitation)**
- If one mechanically constrains a permagnet (permanent magnet) with either a string or plate along one axis, one can create a stable configuration in which the repulsion between the magnets creates a substantial levitation. This is not considered *true* levitation because there is mechanical contact, even though that constraint is usually perpendicular to the vertical levitation axis. A popular toy based on this principle is the Revolution by Carlisle.

Direct Diamagnetic Levitation

A material which is predominantly diamagnetic will be repelled by a magnet, although typical objects only feel a very small force. This can be used to levitate light pieces of pyrolytic graphite or bismuth above a moderately strong permanent magnet. As water is predominantly diamagnetic, this property has been used to levitate water droplets and even live animals, such as a grasshopper and a frog. The magnetic fields required for this are very high, however (in the range of 16 teslas), and create significant problems if ferromagnetic materials are nearby.

The minimum criteria for Diamagnetic Levitation is , $B\frac{dB}{dz} = \mu_0 \rho \frac{g}{\chi}$ where χ = magnetic susceptibilityρ = density of the material$g$ = local gravitational acceleration μ_0 = permeability of free space

B = magnetic field

dB/dz   = rate of change of the magnetic field along the vertical axis (assuming ideal conditions along the z-direction of solenoid magnet)

- Water levitates at B dB/dz » 1400 T2/m Graphite levitates at [B dB/dz] » 375 T2/m

Superconductive levitation

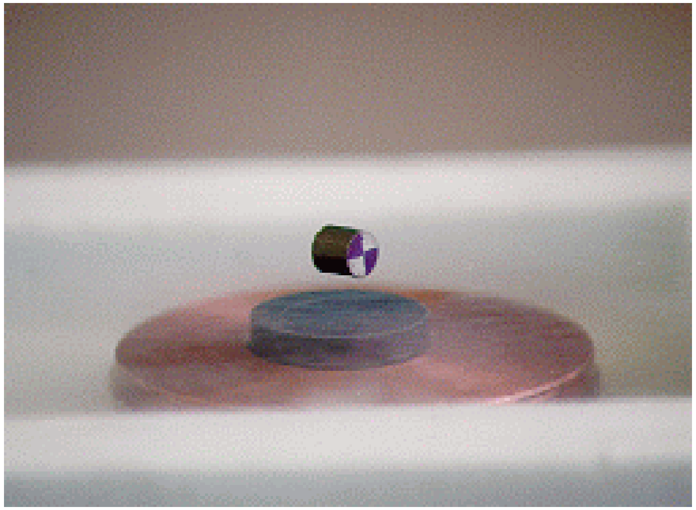
- Superconductors may be considered **perfect diamagnets** ($\mu_r = 0$), completely expelling magnetic fields due to the Meissner effect. The levitmkkuation of the magnet is stabilized due to flux pinning within the superconductor. This principle is exploited by EDS (electrodynamic suspension) in some magnetic levitation trains.
- In trains where the weight of the large electromagnet is a major desing issue, a very strong magnetic field is required to levitate massive train, so superconductors are used.

levitation

High Field
Magnet Laboratory
University of Nijmegen

superconductivity

High Field Magnet Laboratory
University of Nijmegen



Yitrium(1)Barium(2)Copper(3)Oxygen(6.95).
Zero resistance- perfect conductor, perfect diamagnets

Other levitation techniques

- **Rotationally-Stabilized Levitation**

  Spinning a strong permanent magnet in a field created by a ring of other strong permagnets will stabilize it until the rate of precession slows below a critical threshold. This method of levitation was popularized by the Levitron toy. Although "stable", the region of stability is quite narrow both spatially and in the required rate of precession.
- **Servo-Stabilized Electromagnetic Levitation (EMS)**

  Dynamically-stabilized magnetic levitation can be achieved by measuring the position and trajectory of a permagnet to be levitated, and continuously adjusting the field of nearby electromagnets (or even the position of permanent magnets) feedback control systems to keep the levitated object in the desired position.
- This is the principle in place behind common tabletop levitation demonstrations, which use a beam of light to measure the position of an object. The electromagnet (arranged to pull the ferromagnetic object upwards) is turned off whenever the beam of light is broken by the object, and turned back on when it falls beyond the beam. This is a very simple example, and not very robust. Much more complicated and effective measurement, magnetic, and control systems are possible.
- This is also the principle upon which EMS (electromagnetic suspension) magnetic levitation trains are based. The train wraps around the track, and is pulled upwards from below.
- [**Rotating conductors beneath magnets**

  If one rotates a base made of an electrical conductor beneath a permagnet, a current will be induced in the conductor that will repel the permanent magnet. At a sufficiently high rate of rotation of the conductive base, the suspended magnet will levitate. An especially technologically-interesting case of this comes when one uses a Halbach array instead of a single pole permanent magnet.

- **High-frequency Oscillating Electromagnetic Fields**

  A conductor can be levitated above an electromagnet with a high frequency alternating current flowing through it. This causes any regular conductor to behave like a diamagnet, due to the eddy currents generated in the conductor. Since the eddy currents create their own fields which oppose the magnetic field, the conductive object is repelled from the electromagnet.
- This effect requires high frequencies and non-ferromagnetic conductive materials like aluminium or copper, as the ferromagnetic ones are attracted to the electromagnet.
- [**Translational Halbach Arrays and Indutrack**

  Translating Halbach Arrays of NdFeB magnets over conductive loops generates a current in the loop which produces an opposing magnetic field. At some critical velocity the induced magnetic field is strong enough to induce levitation. The Halbach arrays can be placed in a stable configuration and installed, i.e., in a train cart.
- **Halbach arrays**

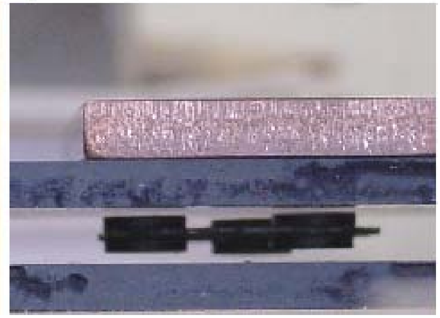
  The Inductrack maglev train system avoids the problems inherent in both the EMS and EDS systems, specially failsafe suspension. It uses only permagnets (in a Halbach array) mounted in the train cart and unpowered conductors in a wired loop installed in a train track to provide levitation. The only restriction is that the train must already be moving at a few kilometers per hour (about human walking speed) to levitate.

  The energy for suspension comes entirely from forward motion, efficiency is good, and no extremely low temperature suspension magnets are required.

  Halbach arrays are also well-suited to magnetic levitation of gyroscope, motor and generator spindles.

Diamagnetic Levitation

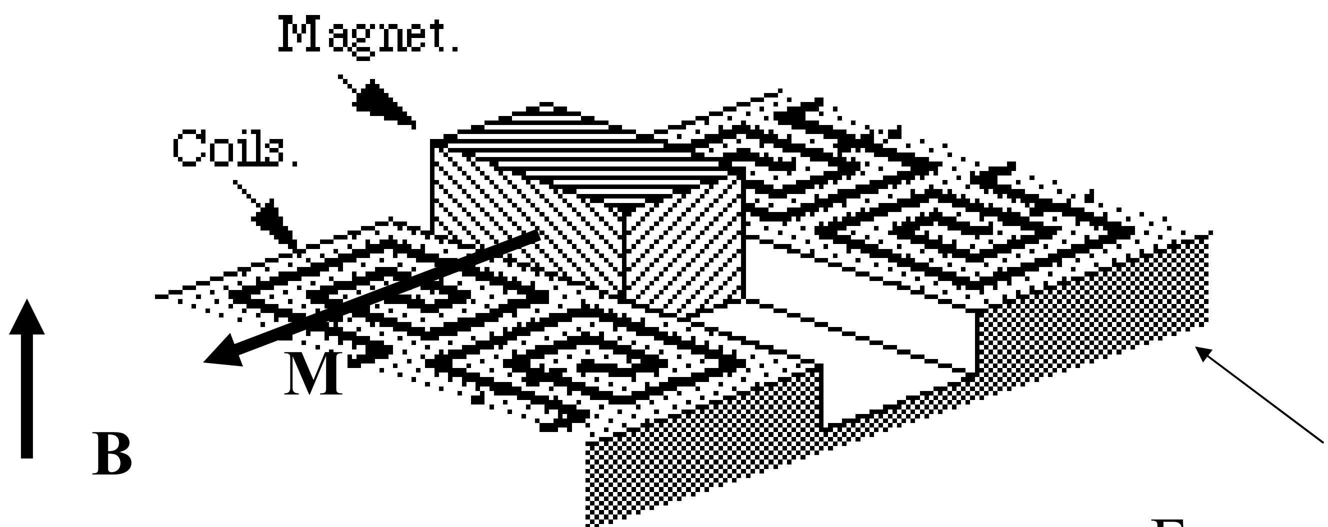
- No energy input required
- Can levitate at room temperature
- Potential applications:
  - Frictionless motor or generator
  -



Levitated magnets

Magnetic micro-actuator

Nickel (commonly used in microactuator)

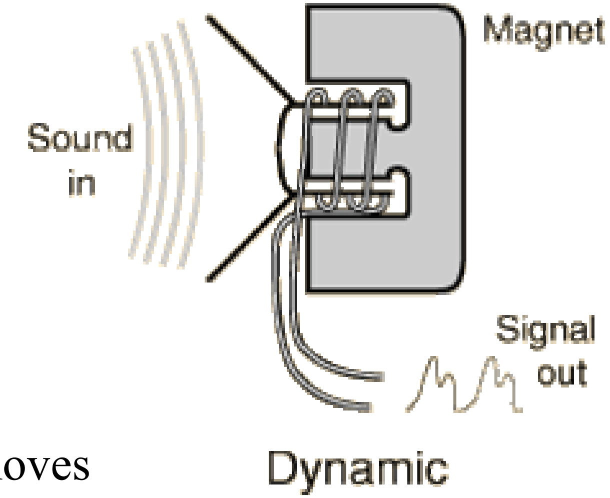


Ferromagnetic material

Magnetic Sensors

- Magneto Dynamic :Dynamic Microphone
- Magnetic field sensor: Eddy current (Hall effect) sensor

Dynamic microphone

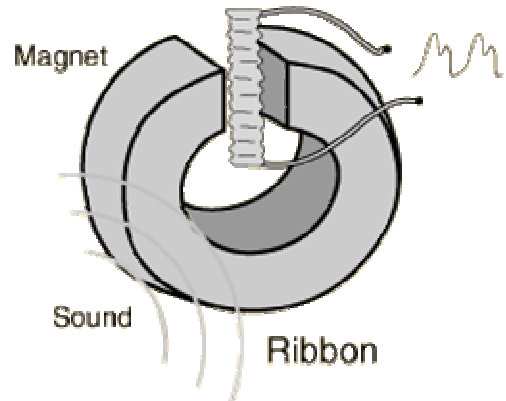


Principle: sound moves the cone and the attached coil of wire moves in the field of a magnet. The generator effect produces a voltage which "images" the sound pressure variation - characterized as a pressure microphone.

Advantages:
•Relatively cheap and rugged.
•Can be easily miniaturized.
Disadvantages:
•The uniformity of response to different frequencies does not match that of the ribbon or condenser microphones

hyperphysics

Ribbon microphone



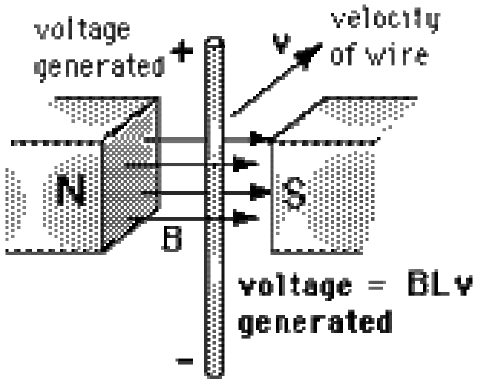
Principle: the air movement associated with the sound moves the metallic ribbon in the magnetic field, generating an imaging voltage between the ends of the ribbon which is proportional to the velocity of the ribbon - characterized as a "velocity" microphone.

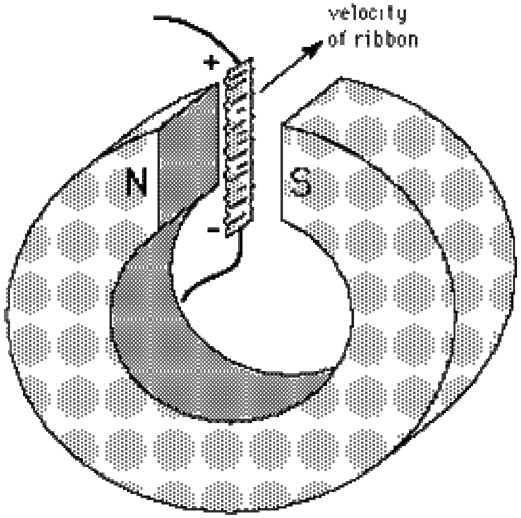
Advantages:
•Adds "warmth" to the tone by accenting lows when close-miked.
•Can be used to discriminate against distant low frequency noise in its most common gradient form.

Disadvantages:
•Accenting lows sometimes produces "boomy" bass.
•Very susceptible to wind noise. Not suitable for outside use unless very well shielded.

hyperphysics

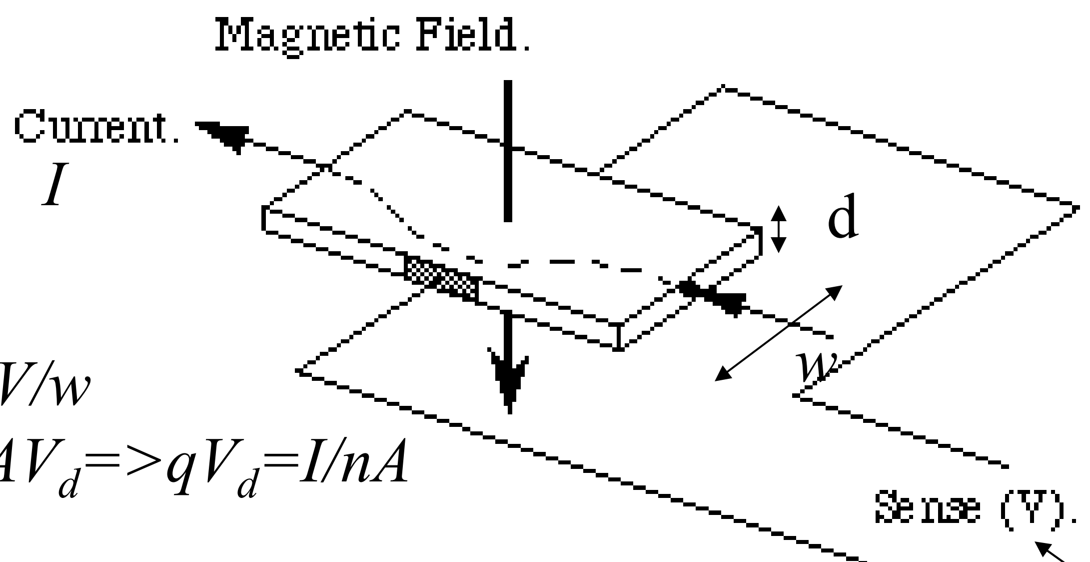
Voltage from Ribbon Microphone





The signal from a ribbon microphone is generated as a motional voltage; the movement of the ribbon in the magnetic field generates a voltage proportional to the velocity of the ribbon.

Magnetic sensor (Hall effect)



$F_e = qE = qV/w$

$I = Q/t = nqAV_d \Rightarrow qV_d = I/nA$

$F_m = qV_dB$

$F_m = Fe \Rightarrow IB/nA = qV/w$

$$\boxed{V = IBw/nqA = IB/nqd}$$

Voltage drop between two contacts

Density of charge carriers

Calculation of the density of free electrons in a metal like copper involves the basic physical data about the metal, plus the fact that copper provides about one free electron per atom to the electrical conduction process. A representative value can be calculated with the following data.

Molar mass of copper = 63.54 gm/mol = 63.54×10^{-3} kg/mol = M

Density of copper = 9 gm/cm^3 = 9×10^3 kg/m^3 = ρ

Number of free electrons per mol = Avogadro's number = 6.02×10^{23} /mol = N_A

Number of free electrons per unit volume = n

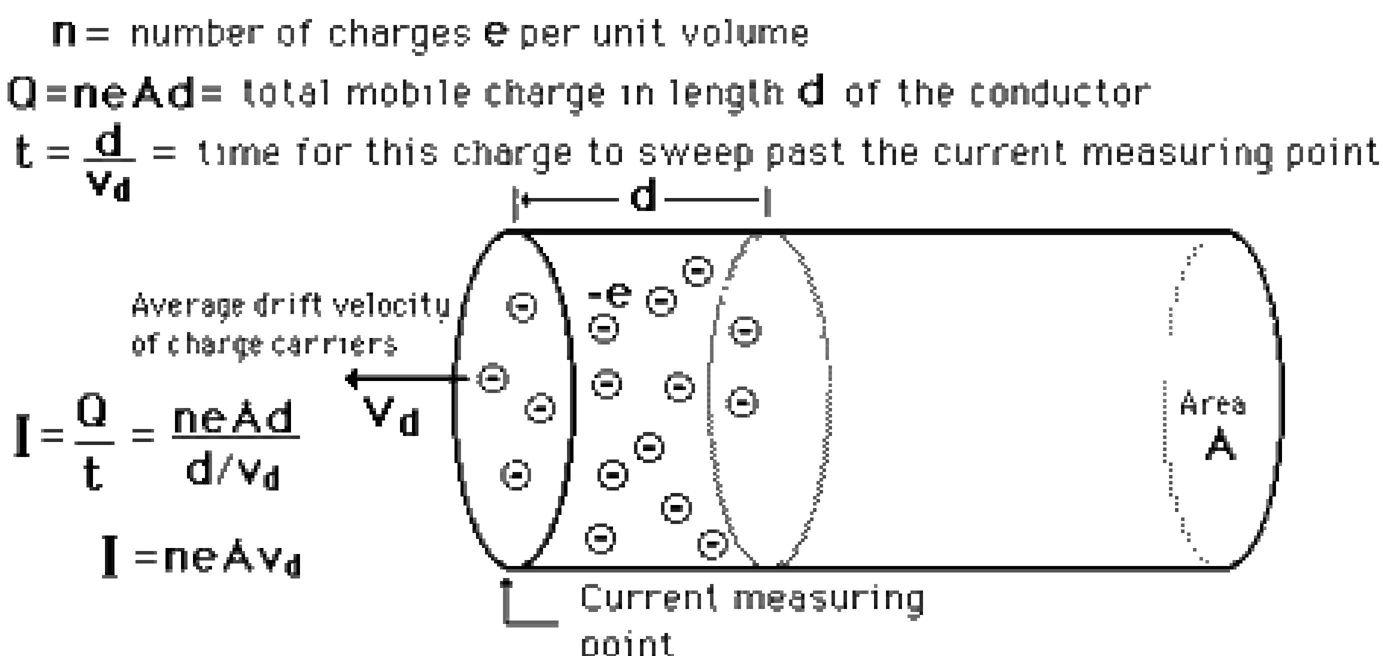
$$= \frac{\text{mass/m}^3 \times \text{atoms/mol}}{\text{mass/mol}} = \text{atoms/m}^3$$

$$n = \frac{\rho N_A}{M} = 8.5 \times 10^{28} \text{ electrons/m}^3$$

This is a nominal value because the density of copper in electrical wiring varies somewhat with processing.

Microscopic Electric Current

Since electric charge is quantized in discrete multiples of the electron charge, it is instructive to look at electric current as the movement of multiple microscopic charge carriers with a drift velocity in a conductor.



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