Magneto-rheological & Magneto-strictive Materials

Corso Materiali intelligenti e Biomimetici
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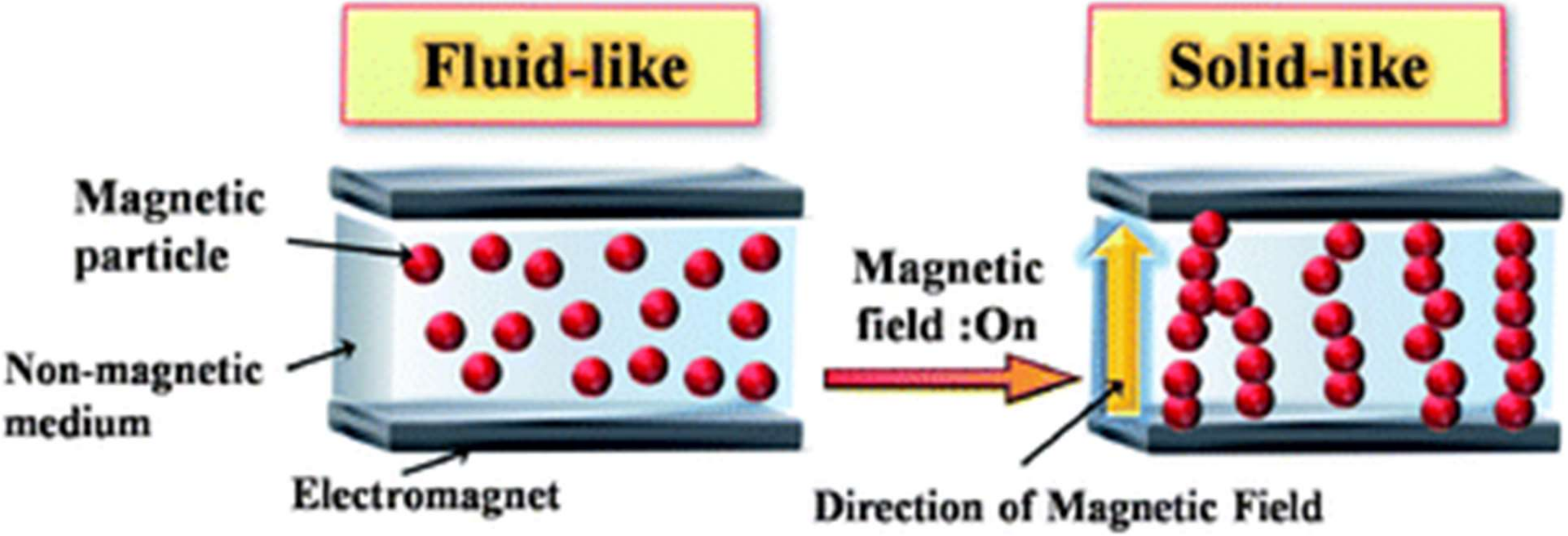
Magneto-rheological (MR) materials

When subjected to a magnetic field, the fluid greatly ***increases its apparent viscosity***, to the point of becoming a viscoelastic solid.

Non colloidal mixture of **ferromagnetic particles** *randomly dispersed in oil or water*, plus some *surfactants* useful to avoid the settling of the suspended particles. MR fluid particles are primarily on the **micrometer-scale** (0.1–10 µm range) and are too dense for Brownian motion to keep them suspended (in the lower density carrier fluid).

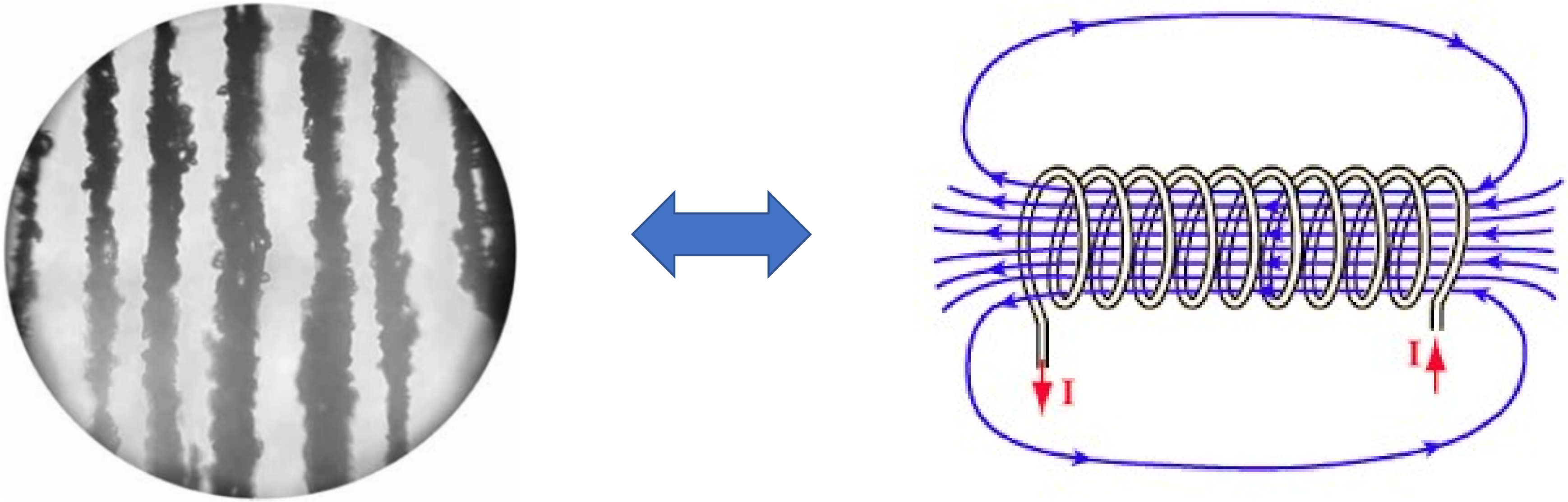
MR materials: behaviour

The ferromagnetic particles feel the magnetic field and their magnetic dipoles align along the lines of magnetic flux. These **microscopic chains** have a the *macroscopic effect to change the apparent viscosity of the fluid*.

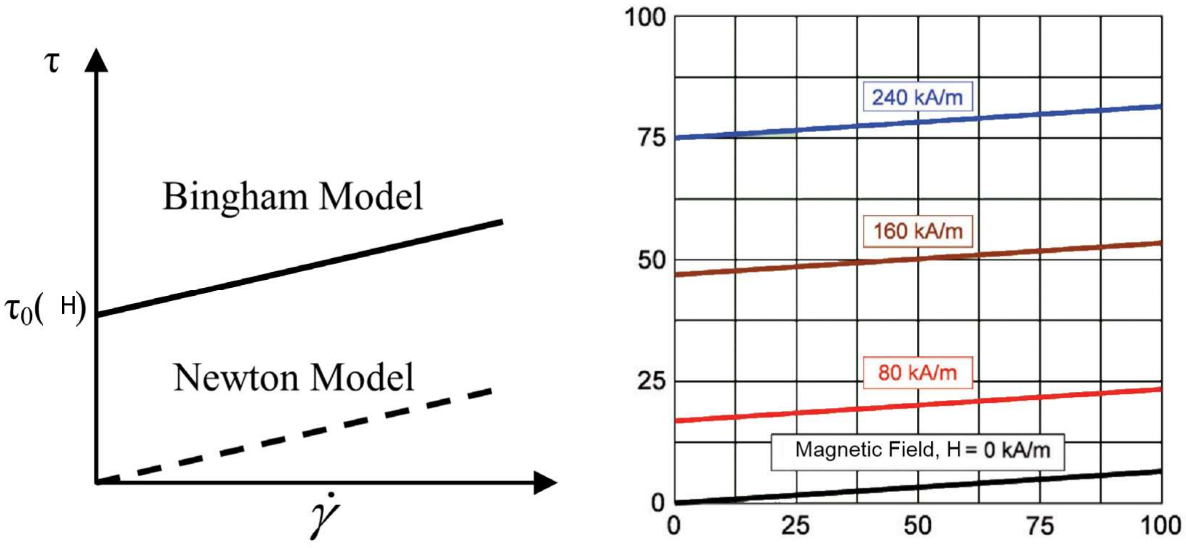


MR materials

The main advantage of MR materials is that the amount of **dissipated energy of the system is simply controllable** by acting on the coil current and the system can provide semi-active behaviour.



MR materials: properties



(a) (b)

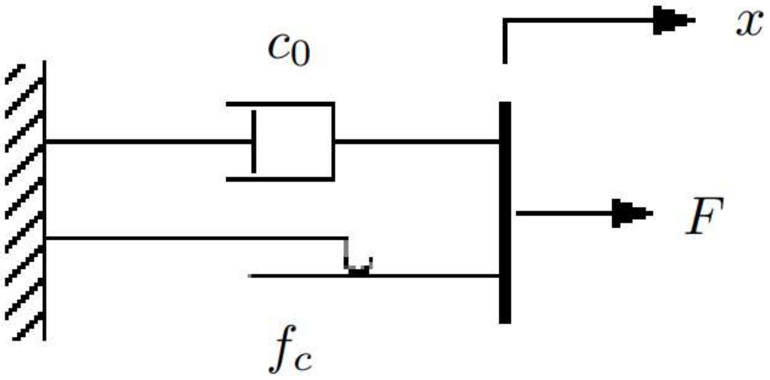
Figure 3: Bingham model of MR fluid (a) and effect of the magnetic field on the yield stress (b).

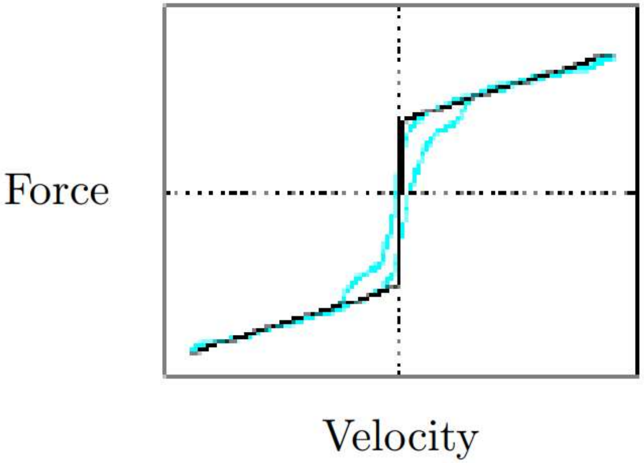
The **yield shear stress** is the main figure of merit of a MR fluid and derives from the non Newtonian behaviour of these fluids.

The MR fluid behaves following a so called **Bingham** law, which means that it exhibits a *non zero shear stress value for a zero shear rate, behaving more like a solid than like a liquid*. The value of the shear stress at no shear rate is called yield stress of the MR fluid and is controlled by the applied magnetic field.

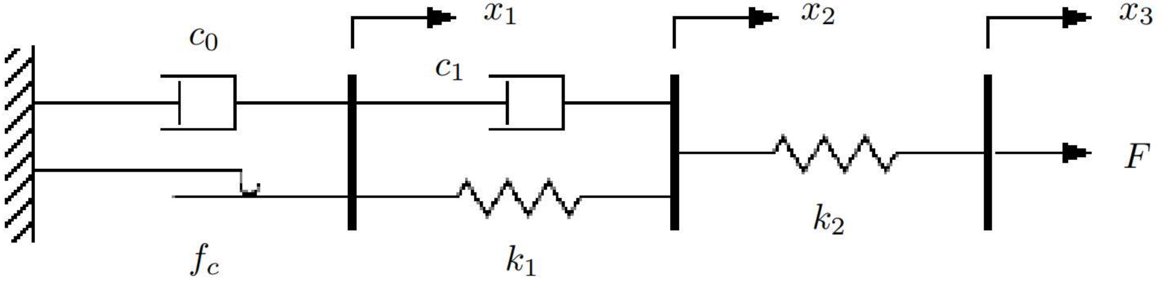
The larger the field, the higher the yield stress. The higher the yield stress **the higher the force the material can withstand without flowing**. Bearing a load is possible only because MR fluids can modify their aggregations states changing from a viscous free-flow liquid to a quasi solid state.

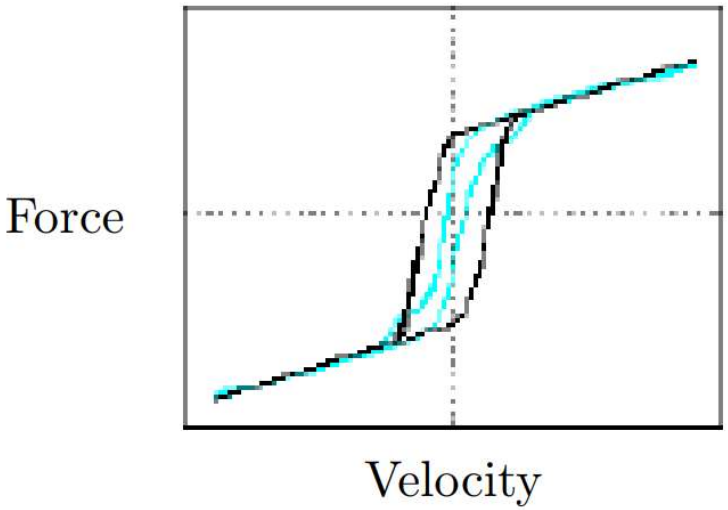
Lumped parameter model 1





Lumped parameter model 2



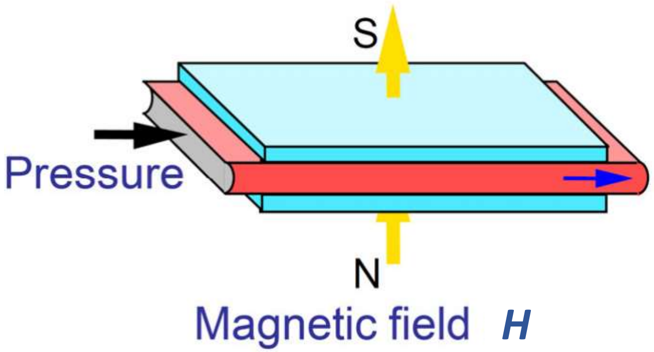


Working modes

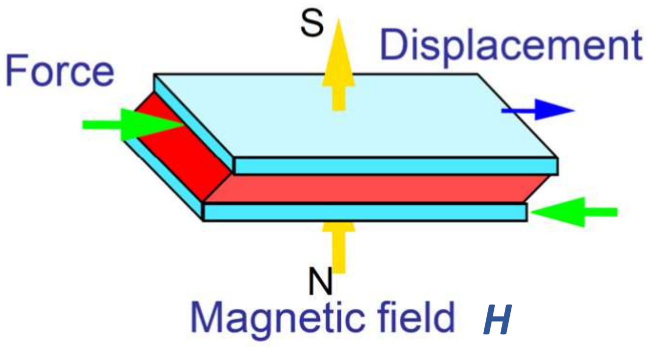
a) **Flow-mode** exploits the *flow between two fixed walls*, the magnetic field is normal to the flow directions and is typical for *linear damper applications*.

b) **Shear-mode** is mainly used in *rotary application* such as brakes and clutches and the fluid is constrained between two *walls which are in relative motion* with the magnetic field normal to the wall direction.

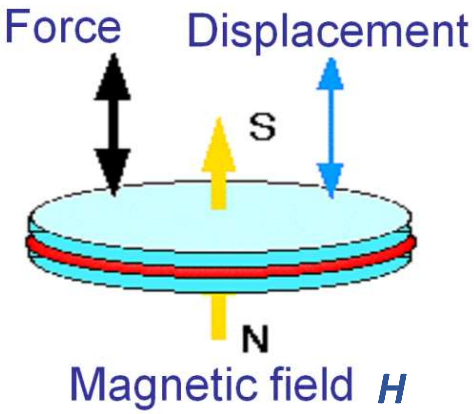
c) **Squeeze-mode** is used mainly for *bearing applications*, is able to provide *high forces and low displacements* having the magnetic field normal to walls directions.



(a)



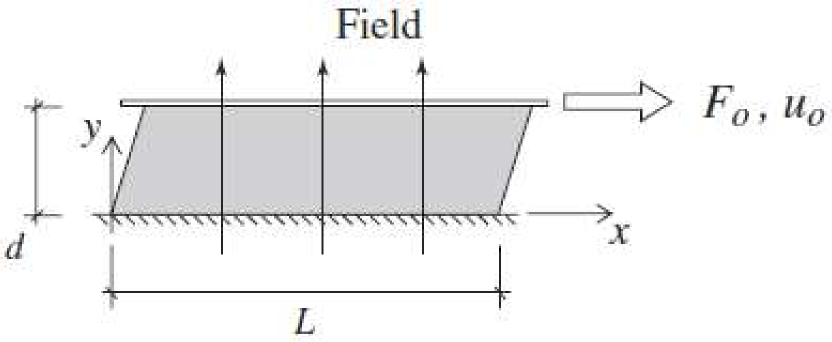
(b)



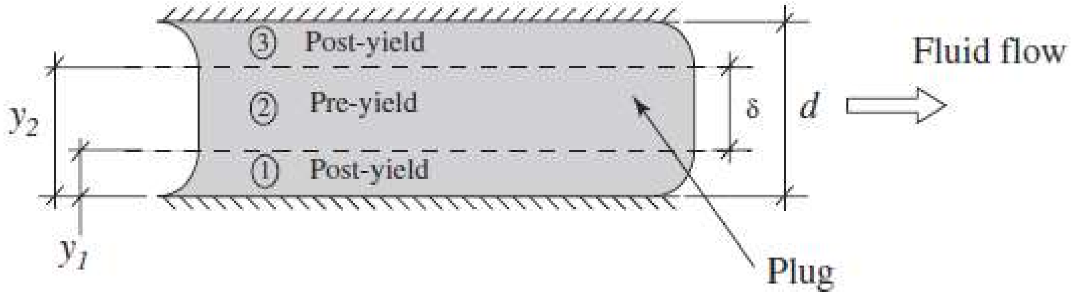
(c)

Calcolo coefficiente smorzamento

Shear-mode operation



Flow-mode operation



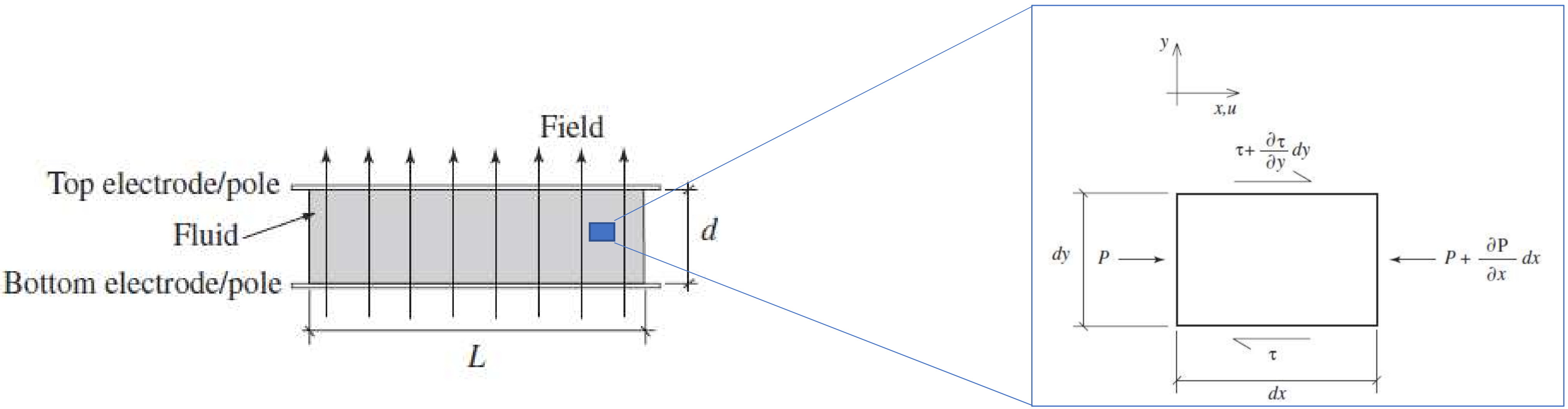
$c = c_0(1 + \mathrm{Bi})$

$c = c_0 \frac{\mathrm{Bi}}{6\bar{\delta}}$

$c_{0\_SM} = \mu\alpha$

$c_{0\_FM} = 12\mu\alpha$

Rectangular Flow Passage:



$$-m\ddot{x} + P\,dy\,b - \tau\,dx\,b - \left(P + \frac{\partial P}{\partial x}\,dx\right) dy\,b + \left(\tau + \frac{\partial \tau}{\partial y}\,dy\right) dx\,b = 0 \quad \Rightarrow \quad \frac{\partial \tau}{\partial y} = \frac{\partial P}{\partial x}$$

Esercitazioni

Gruppo	1	2	3	4	5	6	7	8	9	10	11
1.03 Proprietà Materiali	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
8.03 Polymers&Hydrogels	ok	ok	ok	ok	ok	ok	ok+	ok	ok+	ok	ok
15.03 Piezoelectrics	ok+	ok	ok	ok	ok	ok	ok	ok+	ok	ok	ok+
28.03 MR	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok
29.03 SMA											

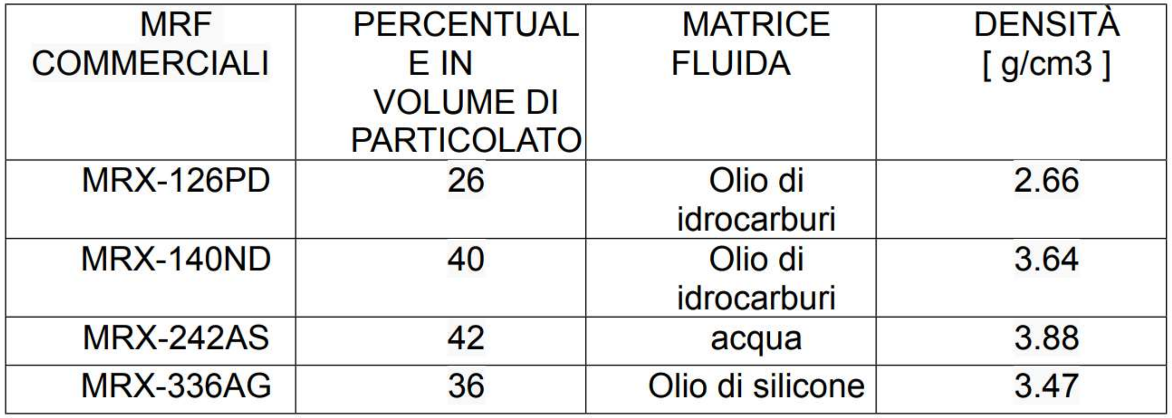
Legenda: ok+ ok ok-

Esercizi

1. Dimensionare spessore (w) smorzatore shear-mode per sostenere F= 100 N @ u=1 m/s note μ=1000 Pa*s, Bi=9, l=100 mm, d=10 mm)
2. Calcolare la F che uno smorzatore flow-mode è in grado di sostenere (d=10 mm, δ= 5 mm, u=1 m/s, c_0= 100 Ns/m, Bi=9)

https://padlet.com/lu_cacopardo/cjhcic1jf2qm

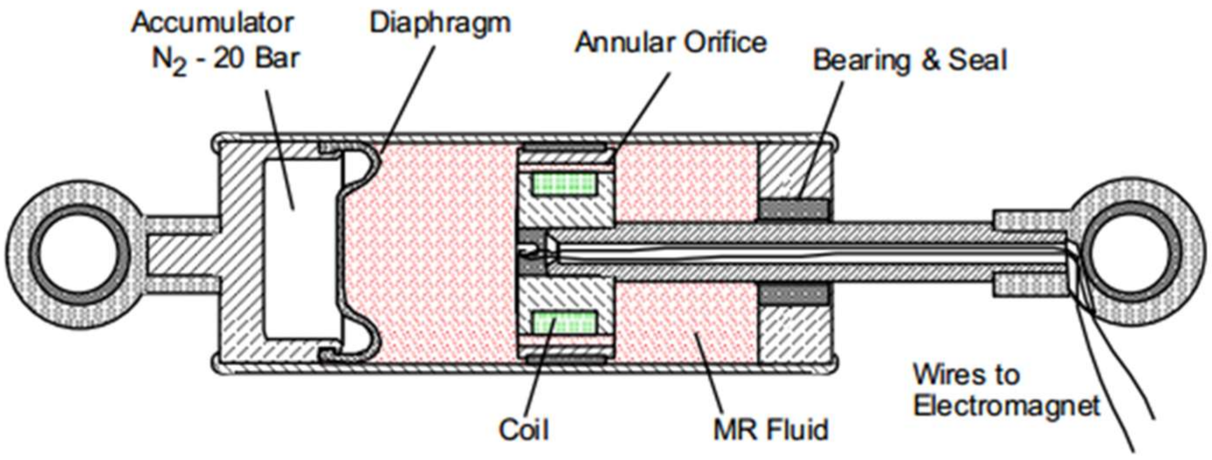
Commercial MR & Limitations

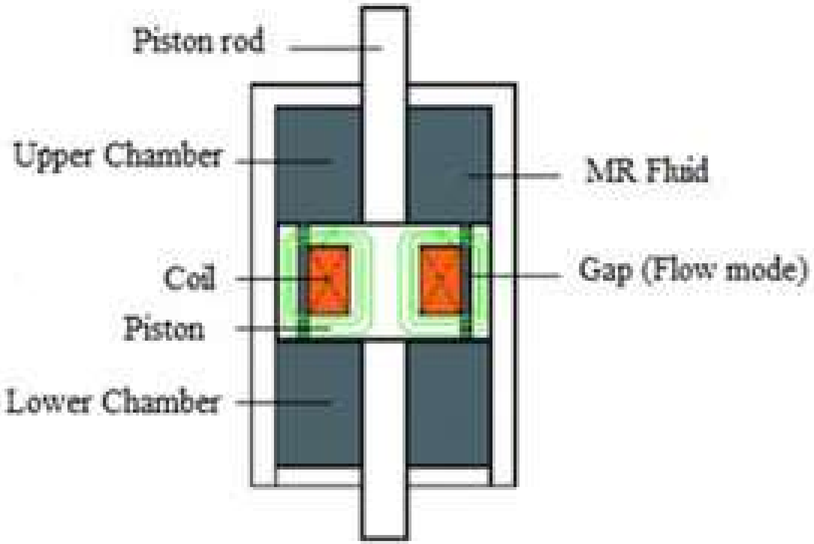


MRF COMMERCIALI	PERCENTUALE IN VOLUME DI PARTICOLATO	MATRICE FLUIDA	DENSITÀ [g/cm3]
MRX-126PD	26	Olio di idrocarburi	2.66
MRX-140ND	40	Olio di idrocarburi	3.64
MRX-242AS	42	acqua	3.88
MRX-336AG	36	Olio di silicone	3.47

- High density, due to presence of iron, makes them **heavy**. However, *operating volumes are small*, so while this is a problem, it is not insurmountable.
- High-quality fluids are **expensive**.
- Fluids are subject to thickening after prolonged use and need **replacing**.
- **Settling of ferro-particles** can be a problem for some applications.

Example of application: Linear Dampers



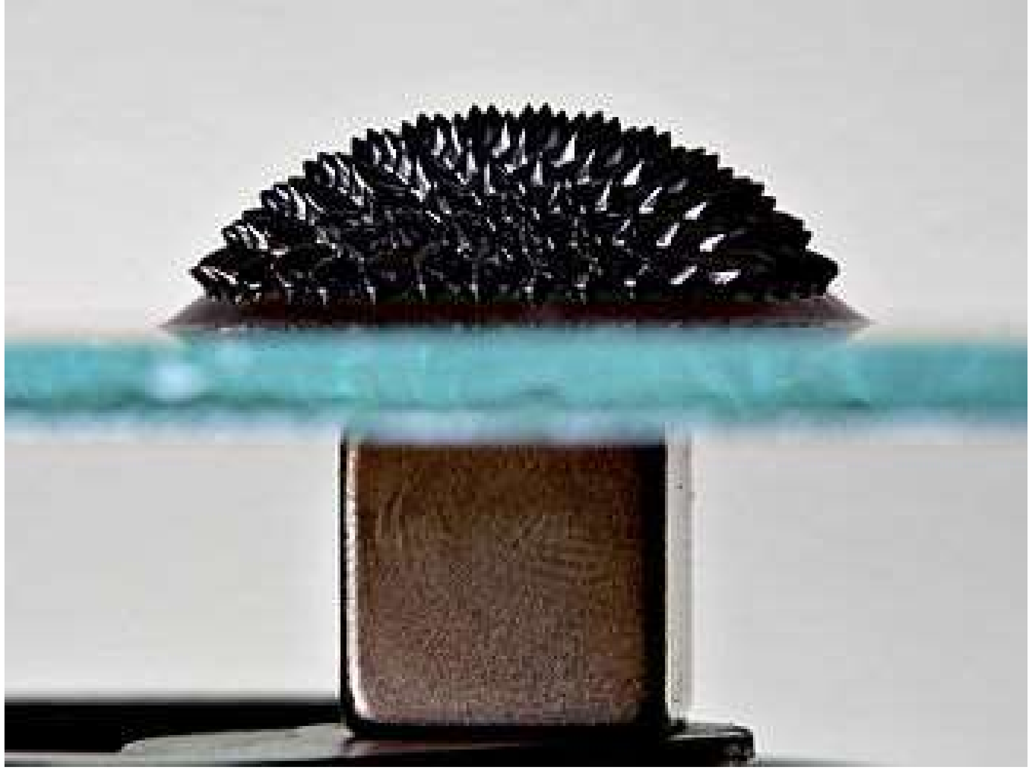


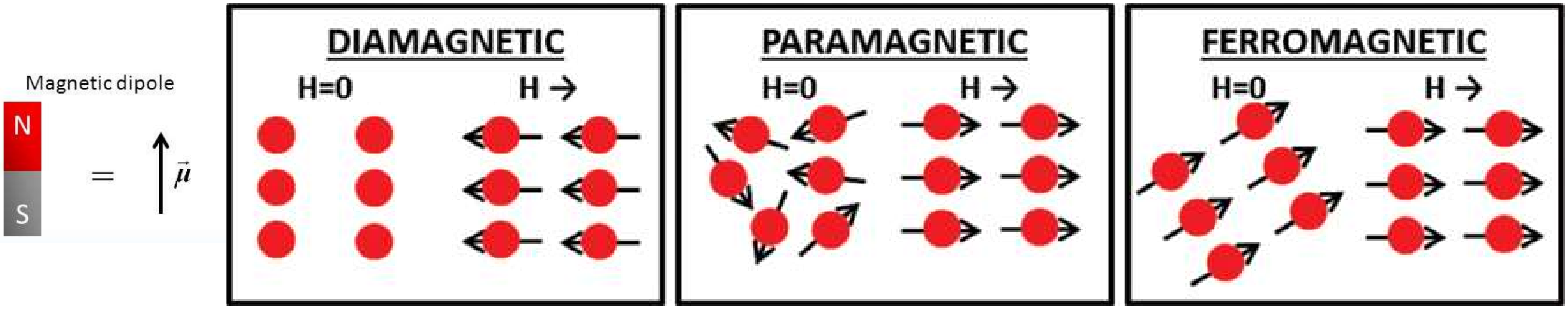
Smart and controllable MR linear dampers: the **desired level of damping** can be obtained **varying the magnetic induction in an orifice between two separated MR fluid chambers**. The orifice acts like a magnetic valve for the fluid, regulated by the current and thus exploits the MR fluid in flow mode.

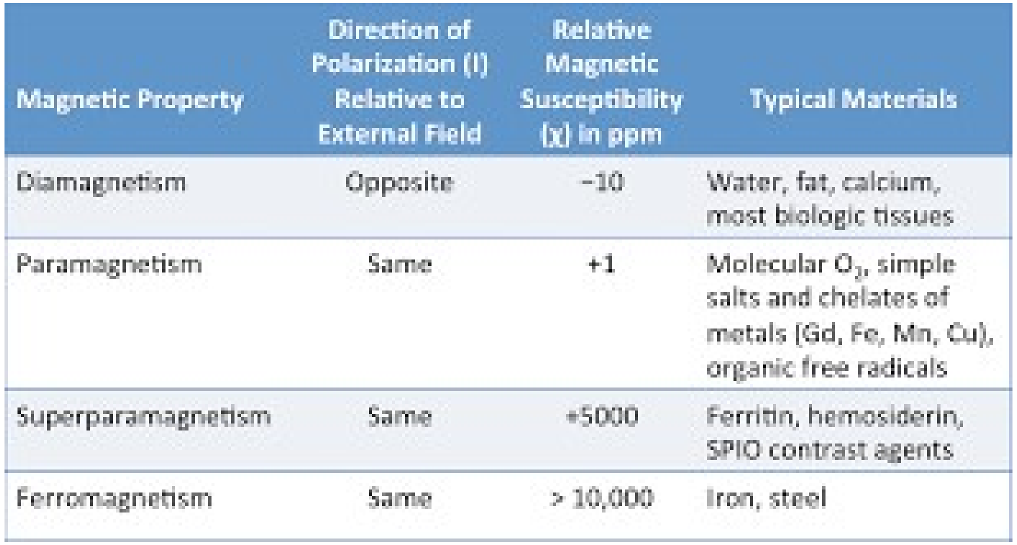
Ferrofluids (FF)

Differently from MR fluids, FF particles are primarily **nanoparticles** that are *suspended by Brownian motion* and generally will not settle under normal conditions.

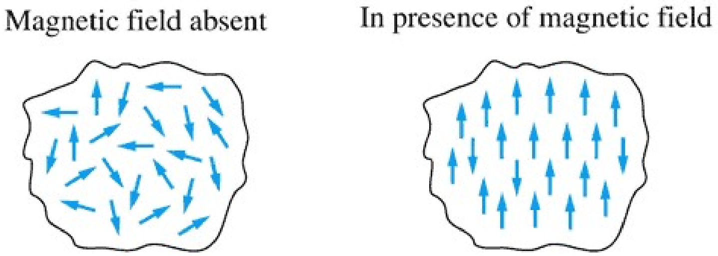
Ferrofluid is **superparamagnetic**, a property that is found *only at the nanoscale*. At the macroscale, ferromagnetic materials are permanently magnetic. But *when ferromagnetic materials are nanometer-sized, they became paramagnetic, which means that they behave like magnets only in the presence of a magnetic field.*



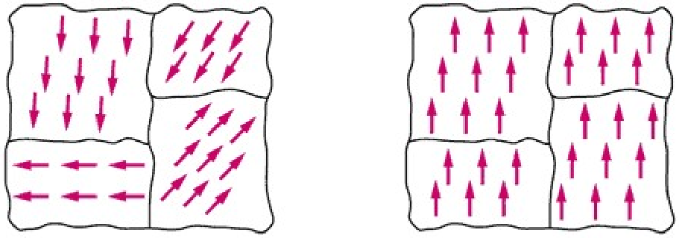




Magnetic Property	Direction of Polarization (I) Relative to External Field	Relative Magnetic Susceptibility (χ) in ppm	Typical Materials
Diamagnetism	Opposite	−10	Water, fat, calcium, most biologic tissues
Paramagnetism	Same	+1	Molecular O_2, simple salts and chelates of metals (Gd, Fe, Mn, Cu), organic free radicals
Superparamagnetism	Same	+5000	Ferritin, hemosiderin, SPIO contrast agents
Ferromagnetism	Same	> 10,000	Iron, steel



Paramagnetism



Ferromagnetism

FF applications

FF **keeps its fluidity** even if subjected to strong magnetic fields**.**

Most applications of magnetic fluid are based on the following of its *properties*:

- It **goes to where the magnetic field is strongest** and stays there;
- It **absorbs electromagnetic energy** at convenient frequencies and *heats up.*

Biomedical Applications:

1) Magnetic drug targeting;
2) Hyperthermia;
3) Contrast enhancement for Magnetic Resonance Imaging;
4) Magnetic separation of cells.

FF - Biomedical Applications

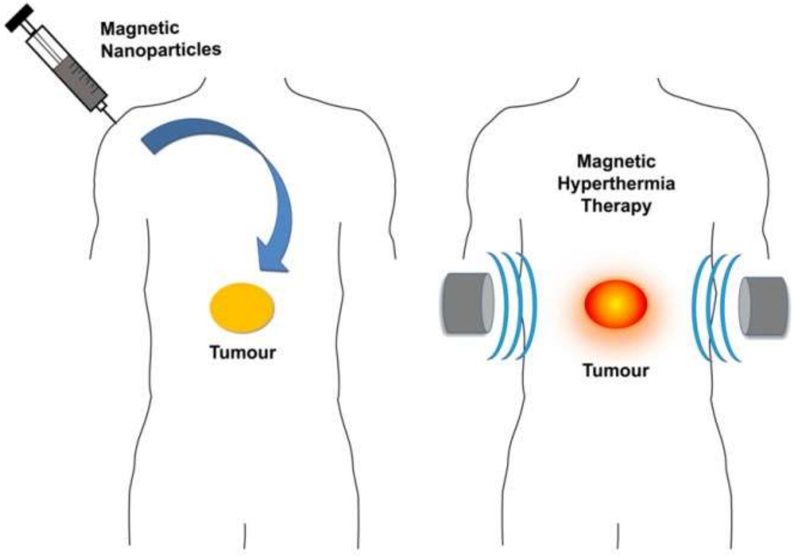
1. Magnetic drug targeting

a **ferrofluid bounded drug** is *injected in a cancer tumor and there it is kept during some time (≈ one hour) by a suitably* **focused magnetic field***.*

The amount of drug necessary is much less than what would be necessary if it were dispersed in the whole body. When the magnetic field is turned off the drug will disperse in the body, but, since the total amount is very small, there will be practically no side effects.

2. Hyperthermia

The property of ferrofluids of **absorbing electromagnetic energy at a frequency that is different from the frequency at which water absorbs energy** allows one to **heat up a localized portion of a living body, where ferrofluid has been injected**, for example a **tumor**, without heating at the same time the surrounding parts of the body.



FF - Biomedical Applications

3. Contrast enhancement for Magnetic Resonance Imaging (MRI)

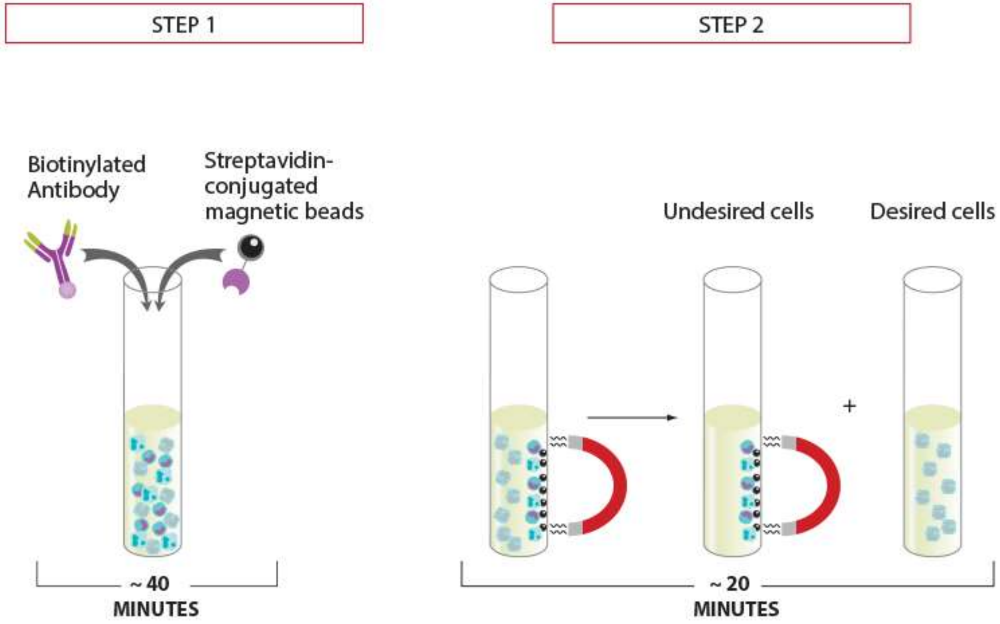
If magnetic particles from a biocompatible **FF are selectively absorbed by some kind of tissue**, this will become **very clearly visible by MRI**.

Dextran coated iron oxides are biocompatible and are excreted via the liver after the treatment. They are selectively taken up by the reticuloendothelial system. This is important because *tumor cells* do not have the effective reticuloendothelial system of healthy cells, so that their relaxation time is not altered by the contrast agent, which makes them distinguishable from the surrounding healthy cells.

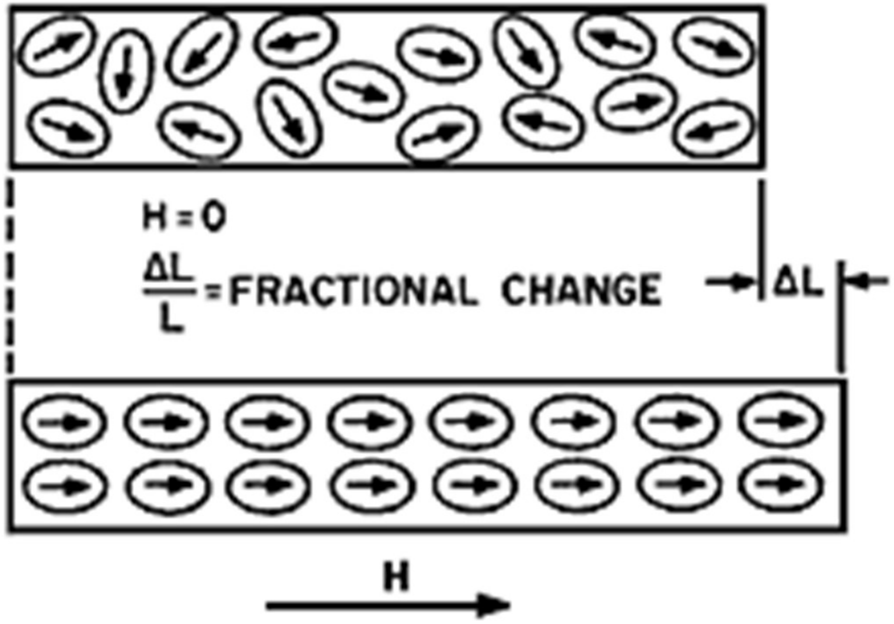
4. Magnetic separation of cells

It is a two-step process: 1) **fixing a magnetic particle to the desired biological entity**, and 2) **pulling the magnetic particles, together with their "prey"** out of the native environment by the action of a magnetic field gradient.

Example: ***cleaning bone marrow from cancer infected samples***, aiming to use the purified samples to be implanted again in the same person. In this case, magnetic nanospheres are coated with monoclonal antibodies having an affinity for the tumor cells. When marrow removed from the patient is put in contact with the coated spheres in a liquid solution, the tumor cells selectively attach to the surface of the spheres, which are then magnetically separated from the solution.



Magneto-strictive materials (MS)



Magnetostriction is a property of ferromagnetic materials that causes them to **change in shape** of materials under the influence of an **external magnetic field**. The cause of magnetostriction change in length is the result of the **rotation of small magnetic domains**.

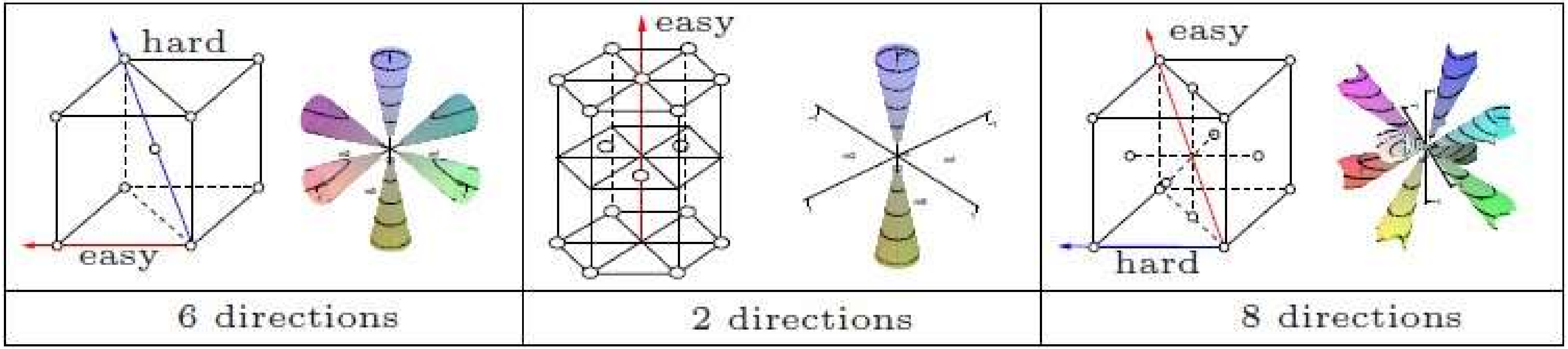
This rotation and re-orientation causes **internal strains** in the material structure. The strains in the structure lead to the **stretching** (in the case of positive magnetostriction) of the material in the direction of the magnetic field.

Magnetostriction

Internally, ferromagnetic materials have a structure that is divided into **domains**, each of which is a region of uniform magnetic polarization. ***When a magnetic field is applied, the boundaries between the domains shift and the domains rotate; both of these effects cause a change in the material dimensions***.

The reason that a **change in the magnetic domains** of a material results in a **change in the materials dimensions** is a consequence of **magneto-crystalline anisotropy**, that *it takes more energy to magnetize a crystalline material in one direction than another*. If a magnetic field is applied to the material at an angle to an easy axis of magnetization, the material will tend to rearrange its structure so that an easy axis is aligned with the field to minimize the free energy of the system.

Since **different crystal directions are associated with different lengths** this effect induces a strain in the material.



6 directions

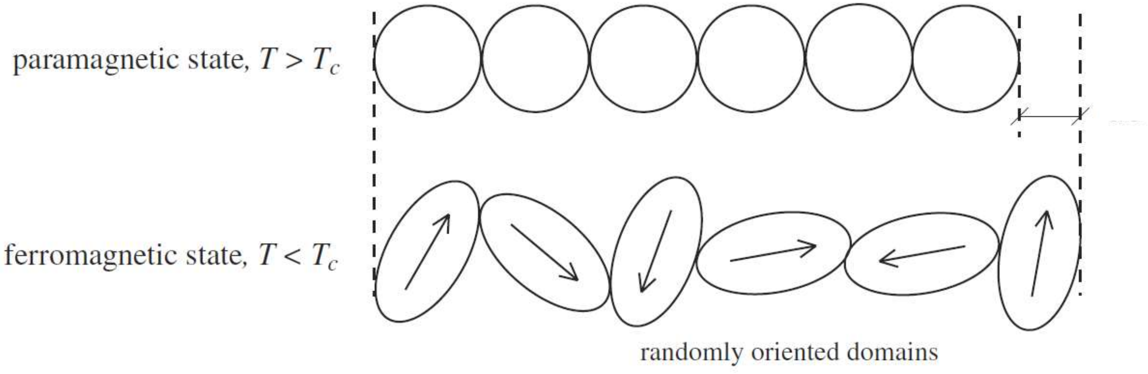
2 directions

8 directions

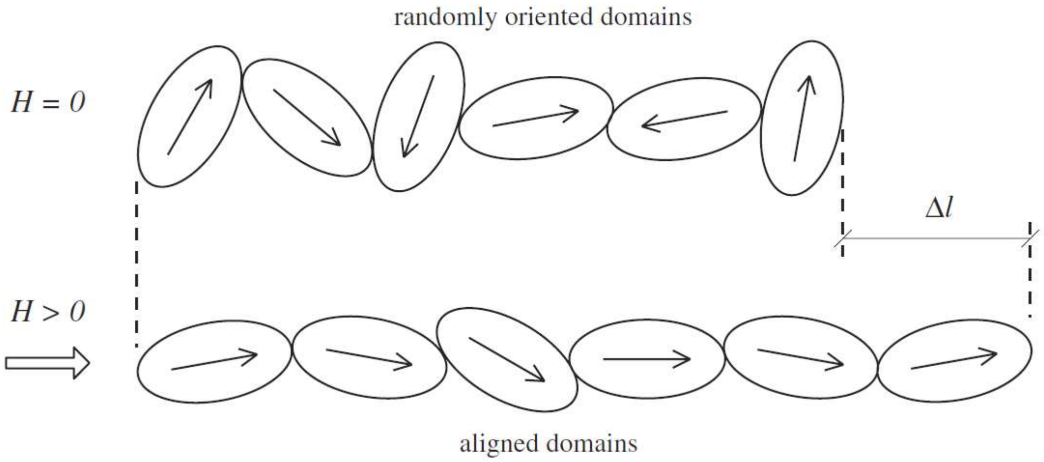
When the material is ***above its Curie temperature***, it exists in a **paramagnetic state** and is composed of **unordered magnetic moments** in random orientations.

On cooling ***below the Curie temperature***, the material becomes **ferromagnetic**, and the **magnetic moments become ordered over small volumes**.

A volume in which all of the magnetic moments are parallel is called a "**domain.**" At this stage, each domain has a **spontaneous magnetization** due to the ordering of the magnetic moments. However, because the domains are randomly oriented, the net magnetization of the material is zero.



(a) Spontaneous magnetostriction



(b) Field induced magnetostriction

Strain vs. Magnetic field

Applying a stronger field leads to stronger and more definite re-orientation of more and more domains in the direction of magnetic field. When all the magnetic domains have become aligned with the magnetic field **the saturation** point has been achieved.

In the region 1–2 ideally there should be an almost **linear relationship between strain and magnetic field**. Because the relationship is a simple one, it is easier to predict the behaviour of the material and so most devices are designed to operate in this region.

Beyond point 2, the **relationship becomes non-linear** again as a result of the fact that most of the magnetic domains have become aligned with the magnetic field direction. At point 3 there is a **saturation** effect, which prevents further strain increase.

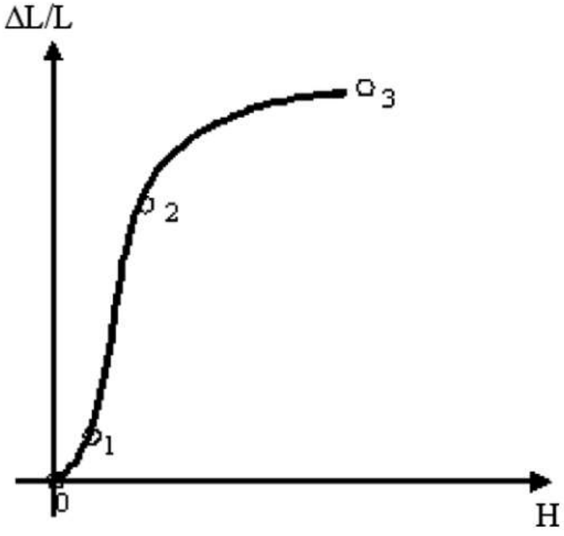


Fig. 1. Strain versus magnetic field.

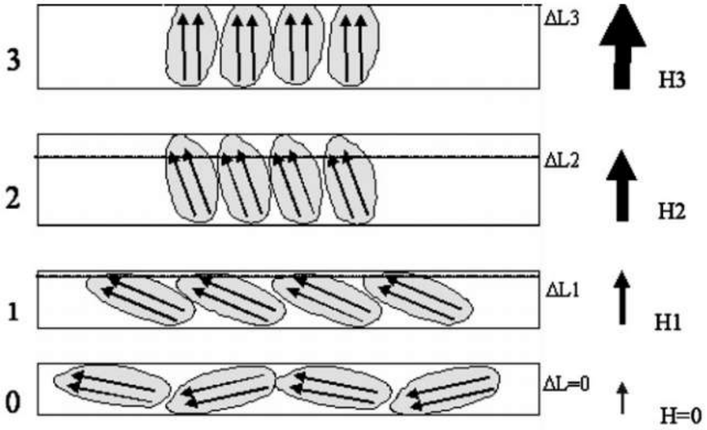
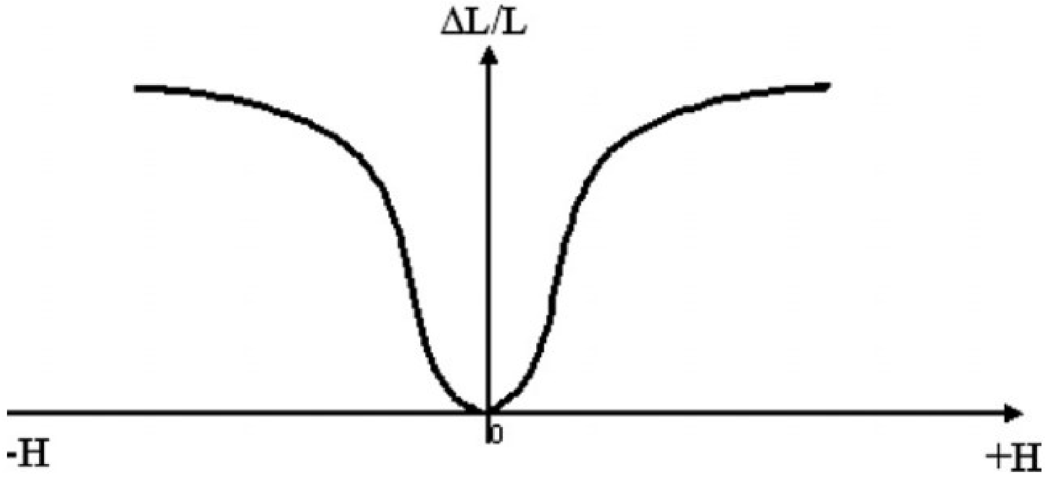
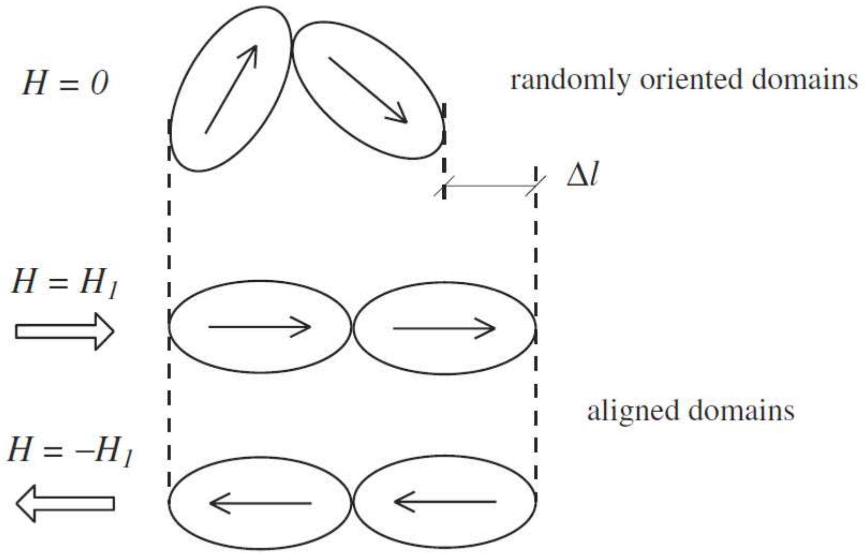


Fig. 2. Strain versus magnetic field, schematically.

Strain vs. Magnetic field (2)

When a magnetic field is established in the opposite direction, the negative field produces the same elongation in the magnetostrictive material, as a positive field would. The shape of the curve is reminiscent of a butterfly and so the curves are referred as **butterfly curves**.

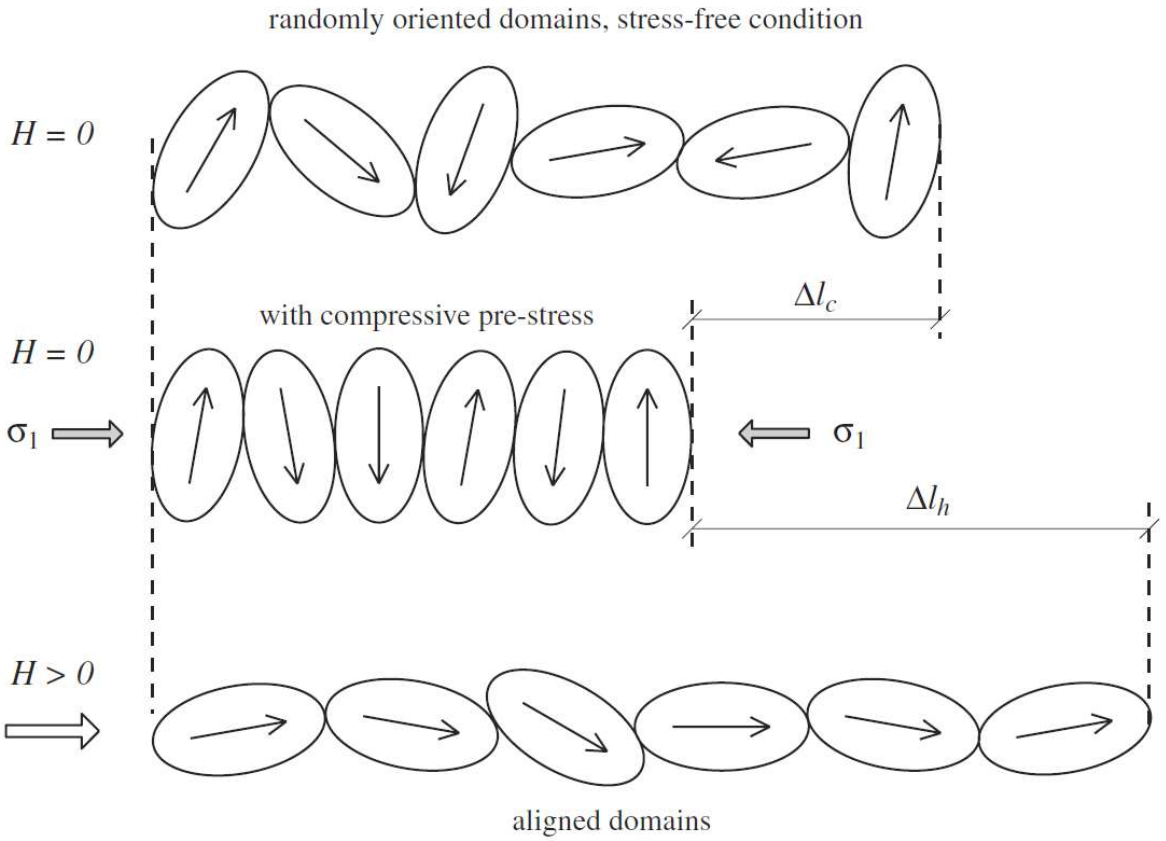


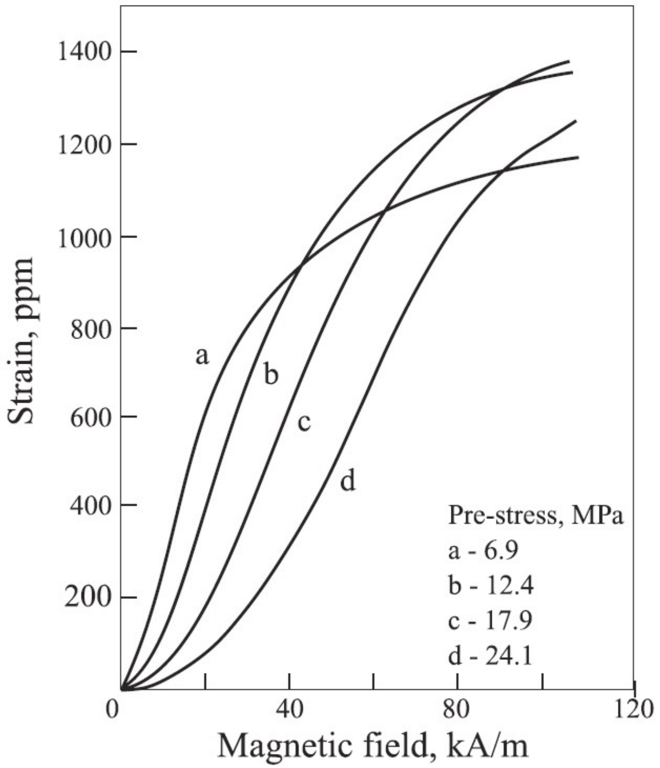


Strain is independent from magnetic field polarity

It can be seen that if the material is given an initial **compressive pre-stress**, the *recoverable strain is larger than in the case of zero compressive pre-stress*.

However, at high values of compressive prestress, the material is unable to respond by the same extent to the applied magnetic field, and the induced strain starts to decrease. Therefore, **the best performance can be achieved by operating the material at a moderate value of compressive prestress**.

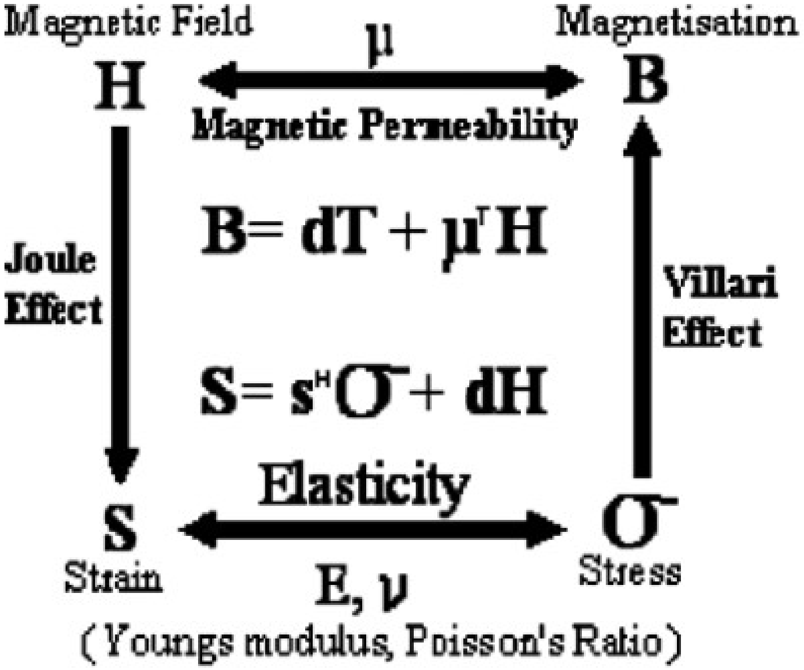




(Main) Magnetostrictive Effects

Magnetostriction is, in general, a reversible exchange of energy between the mechanical form and the magnetic form.

The **Joule Effect** consist in the **expansion**, *positive magnetostriction*, **or contraction**, *negative magnetostriction,* of the material.
In the absence of the magnetic field, the sample shape returns to its original dimensions.



The Villari Effect is a **change of the magnetic susceptibility** (response to an applied field) of a material when **subjected to a mechanical stress**.
There is a change in the magnetic flux density which flows through the sample as a result of the creation of a magnetic field. The change in flux density can be detected by a pickup coil and is proportional to the level of the applied stress.

$$V = -NA\frac{dB}{dt}$$

Example of MS materials

- **Cobalt** exhibits a room-temperature magnetostriction of *60 microstrains*.
- Cobalt alloys: **Terfenol-D**, (Ter for terbium, Fe for iron, NOL for Naval Ordnance Laboratory, and D for dysprosium) exhibits about *2000 microstrains* in a field of 160 kA/m at room temperature and is the most commonly used engineering magnetostrictive material.
- **Metglas** 2605SC (amorphous alloy $Fe_{81}Si_{3.5}B_{13.5}C_{2)}$. Favourable properties of this material are its *high saturation-magnetostriction constant* of about *20 microstrains* and more, coupled with a low magnetic-anisotropy field strength, H_A, of less than *1 kA/m* (to reach magnetic saturation).

MS properties

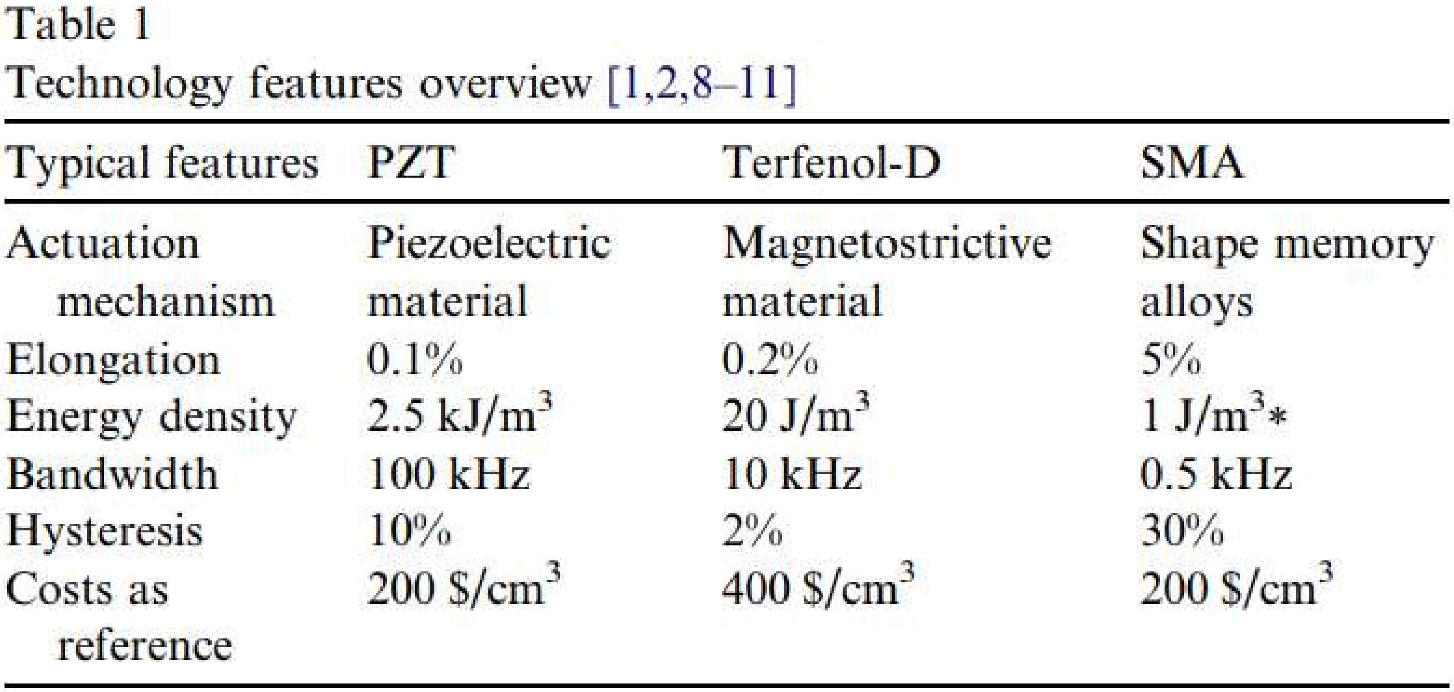
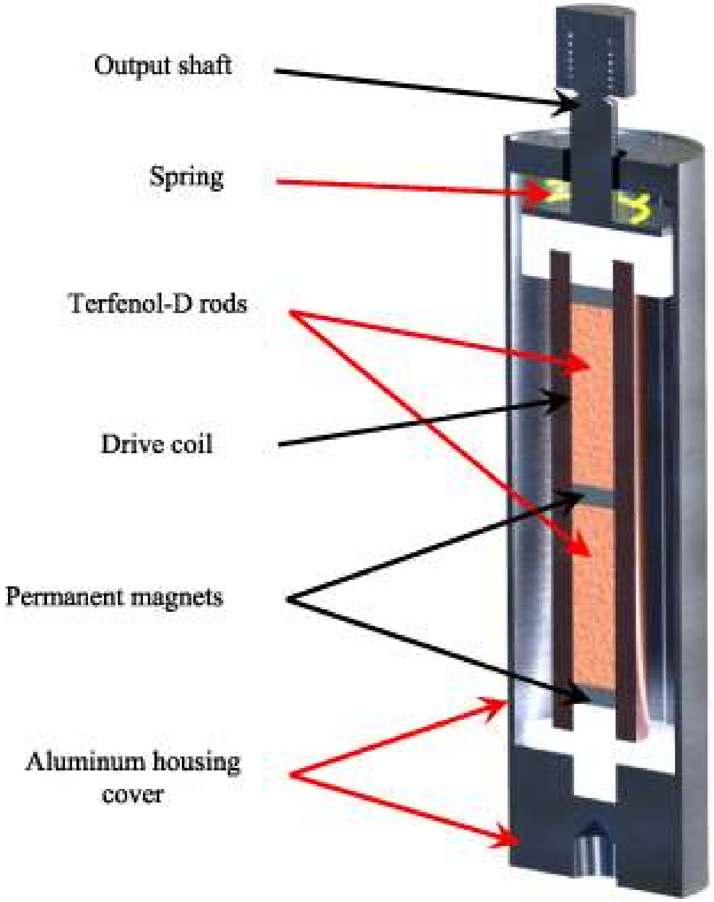


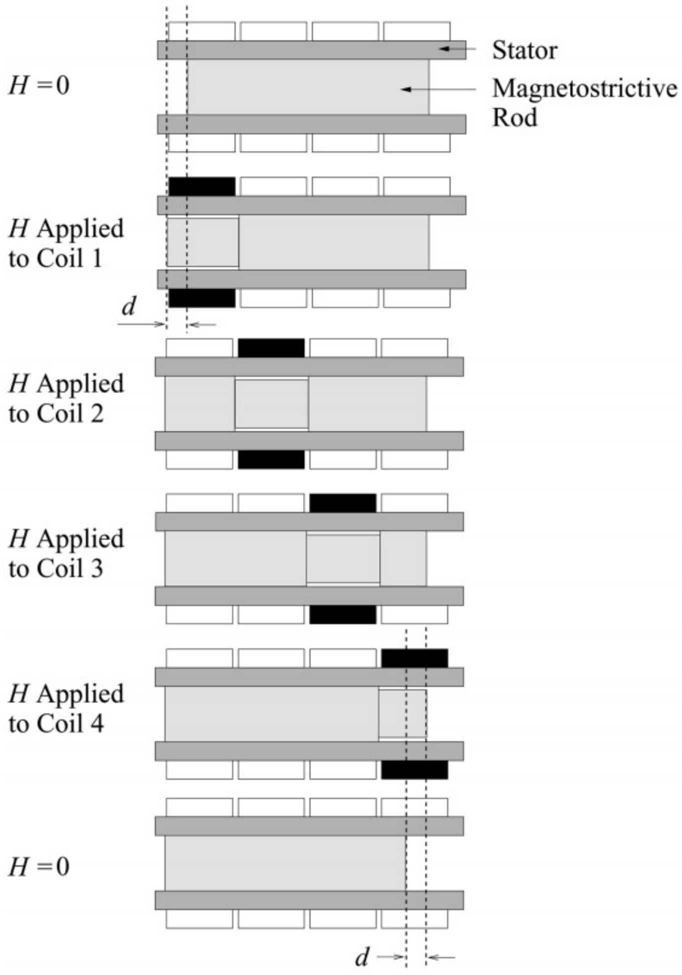
Table 1
Technology features overview [1,2,8–11]

Typical features	PZT	Terfenol-D	SMA
Actuation mechanism	Piezoelectric material	Magnetostrictive material	Shape memory alloys
Elongation	0.1%	0.2%	5%
Energy density	2.5 kJ/m^3	20 J/m^3	1 J/m^3*
Bandwidth	100 kHz	10 kHz	0.5 kHz
Hysteresis	10%	2%	30%
Costs as reference	200 \$/cm^3	400 \$/cm^3	200 \$/cm^3

Application example: MS actuator



Application example(2): MS inchworm motor



When one of the coils is energized, the section of rod directly exposed to the magnetic field **elongates and shrinks**.
As the field is removed, the **rod clamps itself again inside the stator** but at a distance *d* to the left of the original position.
As the remaining coils are energized sequentially and the magnetic field profile is swept, *the rod moves in the direction opposite to the sweeping field*. The direction of motion is changed by inverting the sequence in which the coils are energized.