Magnetic materials and configurations for linear actuators

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1 Magnetic force vs Lorentz force based actuators

When the objective is to obtain force from a magnetic field, there are two options: using the attraction between magnets or using the Lorentz force. To generate a force from a controlled electric current, there are three different electromagnetic phenomena that can be exploited: the Coulomb, magnetic and Lorentz forces. Magnetic force has more applications in electric actuators. Therefore, in this thesis Lorentz force will be only compared with magnetic force and Coulomb force will be considered out of the scope of this thesis.

A magnetic force is present when the magnetic field of two different elements shares a common space. These magnetic fields can be originated in ferromagnetic, paramagnetic o diamagnetic materials when excited from an external magnetic field. Magnetic fields can also be produced by electric currents in vacum and magnetized materials with a significant remanence. In an actuator based on magnetic forces, those fields must be controlled. Therefore, an electric current will be needed either to generate the field by itself or to excite a material with magnetic properties. The Lorentz force also needs an electric current to have a non zero value. Those currents that will control the actuation must be applied from an external power source, so both methods can be compared in terms of power consumption. It will be demonstrated that using the magnetic force is, in some sizes, worse than using the Lorentz force in a relevant aspect, energy efficiency.

Both forces, the Lorentz force and the magnetic force, depend directly of magnetic field ($\vec{B}$) so high fields with low energy consumption are desirable. The magnetic field ($\vec{B}$), is related to the magnetic field intensity ($\vec{H}$) by magnetic permeability (μ). To activate a force between magnets, the magnetic field is actively produced in electromagnets by applying energy from an external power source. In Lorentz force, the magnetic field will be considered present without any energy consumption in this comparison because of the use of permanent magnets. Some possible field sources are presented hereafter. Superconducting electromagnets are not considered since they need to be refrigerated, and they will consume more energy than non refrigerated electromagnets. The highest fields are reached in extremely short pulses (Nakamura et al., 2018). Nevertheless, those fields will neither be considered because will limit the possibilities of the actuation to very short periods of time. The strongest continuous man-made magnetic field is of 45 T (National High Magnetic Field Laboratory, 2018). It is produced in a bitter electromagnet whose resistive part, which does not need superconducting refrigeration, produces 33.5 T. Nevertheless, bitter electromagnets have a high power consumption. This is because the magnetic field is generated in the air, which has low magnetic permeability (μ). The biggest forces cannot be reached by the highest power efficiency in electromagnets. If materials with higher magnetic permeability are used in electromagnets (e.g. iron) there is a saturation field above which any added power will not produce higher $\vec{B}$ fields. This behaviour is explained by a variable magnetic permeability with $\vec{H}$ field in ferromagnetic materials (Bozorth, 1993). Therefore, high permeability materials set a superior limit to the B value. Nevertheless, as energetic efficiency is being compared, fields produced in those materials are going to be considered, being the most efficient way to activate a $\vec{B}$ field.

To compare the energy consumption of Lorentz and magnetic forces, it is assumed that the electric current flows in the same conductor so resistivity will be the same in both phenomena. Therefore, the energy consumption comparison is equivalent to the electric current comparison. The magnetic force between two magnetic field sources is maximum when they are placed together. Assuming that they are equal electromagnets with the same $\vec{B}$, the total force for both magnetized surfaces obtained using the Maxwell stress tensor, is defined by Equation 1.

$$F = \frac{B^2 A}{\mu_0} \; [N] \tag{1}$$

where A is the area of each surface and μ_0 is the permeability of space. To maximize the force and minimize the consumption, the surface of the electromagnets placed together must be a circle. This is because the maximum possible area of a perimeter l is gotten from a circle of area $A = \frac{l}{2\pi}^2$ and minimizing the perimeter minimize the resistivity and thus the consumption. It is important to point out that the force decreases at least proportionally to the square of the distance between the electromagnets.

Furthermore, the current needed to generate the B value in an electromagnet, obtained using Biot-Savart law, is defined in Equation 2.

$$B = \mu n I \; [T] \tag{2}$$

where n is the density of turns per length of the conductor and I the electric current through that conductor.

As aforementioned, higher permeability materials produce $\vec{B}$ fields with less energy consumption. Therefore, Metglas 2714A is chosen as the material looped with the electric current to generate the $\vec{B}$ field. It is the most efficient way to produce a magnetic field because it has the highest magnetic permeability $\mu_C = 1.256 \, \frac{H}{m}$ (Metglas®, Inc., 2018), which sets a superior limit in power efficiency. Nevertheless, Metglas 2714A has a saturation induction of $B_C = 0.57 \; T$. Therefore, the maximum force obtained at the maximum energy efficientcy is:

$$F_C = \frac{B_C^2 l^2}{4\pi\mu_0} = 20574.532 \; l^2 [N] \tag{3}$$

Taking that into account, the necessary current I to produce the maximum B value by means of two coils of $n = 1$ with magnetic permeability of Metglas 2714A is $I = 2\frac{B_C}{\mu_C} = 0.907 A$.

In permanent magnet configurations, highest $\vec{B}$ fields are reached in Halbach configurations. These configurations consist of a rotation of the magnetization of a material along a path or a surface. This rotation, if correctly defined, augments the B value on one side while practically cancelling the field to near zero on the other side. If the rotation is made along a straight line, the configuration is called Halbach array (shown in Figure 1). When the rotation is done along a circumference, the resulting configuration is called Halbach cylinder (shown in Figure 2). Lastly, if this Halbach cylinder magnetization is generalized as the meridians of a sphere the resulting configuration is called Halbach sphere.

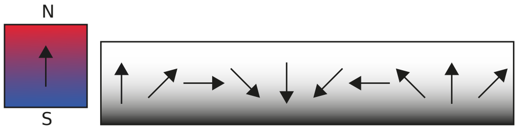


Figure 1: Magnetization pattern in a Halbach Array.

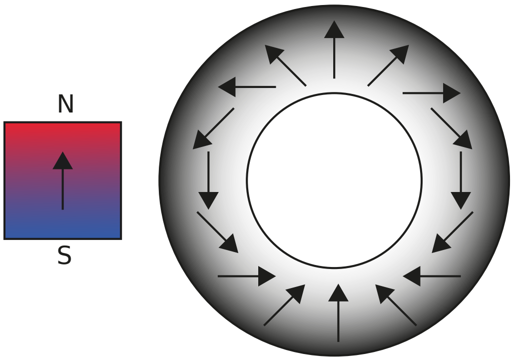


Figure 2: Magnetization pattern in a Halbach Cylinder.

Higher B values $B_X = 5\ T$ (CERN Courier, 2002) are obtained in Halbach spheres configurations. However, these configurations are not easy to make. Therefore, the analysis carried out is done with a Halbach cylinder, which can easily provide fields of $B_Y = 1\ T$.

The force produced in an actuator by the Lorentz force is calculated by Equation **??**. Considering the same length of the wire (l), as the perimeter of the current loop of an electromagnet, the same I and a magnetic field B_Y, the force is:

$$F_Y = B_Y\ I\ l = 0.907\ l\ [N] \tag{4}$$

Therefore, at equal power consumption, the force between two electromagnets is always lower if $20574.532\ l^2 < 0.907\ l$, which means sizes of:

$$l < 4.408\ 10^{-5}\ m \tag{5}$$

That result sets a point in length from which Lorentz force based actuators are always more energetically efficient than usual electromagnets devices.

With this limit, building actuators that surpass the energy efficiency of Metglas 2741A looks discouraging. However, if the technology is able to get those small sizes, some configurations explained in the following sections can be used to overcome those small sizes. It is important to notice that if the actuator moves through a path, which is essential to develop a work, the force of electromagnets will decrease at least with the square of the distance between the electromagnets. This is not the case in Lorentz force based actuators which force is constant through a path contained in a Halbach cylinder.

2 Magnetic structure

The magnetic structure will generate the higher possible $\vec{B}$ field in a direction as perpendicular as possible to the current $\vec{I}$ flowing through the inner conductor.

The wire carrying current density will be considered rigid and will only be allowed to move in one dimension. Therefore, the $\vec{B}$ field has to be a constant vector field in order to generate a force that varies linearly with the current. In order to choose the magnetic configuration, cost, inner B value and mass are considered the most important parameters to optimize. Low cost is important because resources for this thesis are limited. Inner B value have to be as high as possible to ease the observation and measure of the Lorentz force in the actuator. Mass is important since this actuator is meant to imitate a muscle and useful muscles must develop enough force to lift themselves. Therefore, the lighter the Lorentzito the easier it will be to implement an artificial muscle.

To sum up, high $\vec{B}$ field and low mass cheap structures are sought. These characteristics can be obtained by a Halbach cylinder configuration (Halbach, 1985). A Halbach cylinder is a hollow cylinder made of oriented magnetization pattern, defined by Equation 6, whose coordinates are defined in Figure 3a.

$$\vec{M} = M_r[cos((k-1)(\phi - \frac{\pi}{2}))\hat{\rho} + sin((k-1)(\phi - \frac{\pi}{2}))\hat{\phi}] \tag{6}$$

A uniform inner field is given when $k = 2$, that sets an inner field defined by Equation 7.

$$\vec{H} = M_r ln(\frac{R2}{R1})\hat{y} \tag{7}$$

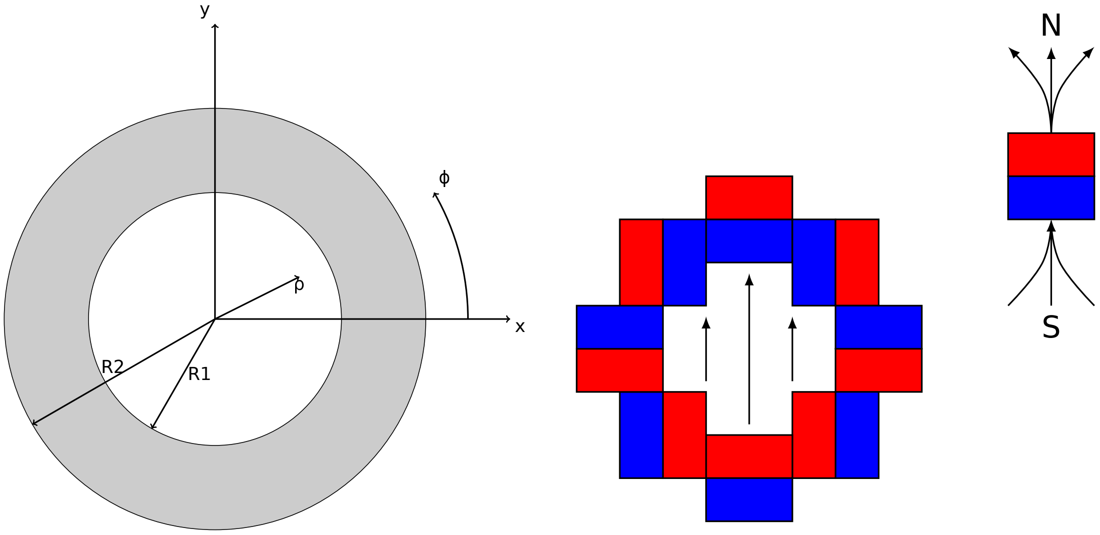
Those configurations can also grant a small value of B outside a certain region enhancing the magnetic isolation between actuators which is relevant if placed together. It is important to poit out that, given a non infinite length, Halbach cylinders are affected by end effects which will curve the inner field at the base of the cylinder.

Halbach spheres are the three dimension generalization of Halbach cylinders. Its inner field given by $k = 2$ is defined by Equation 8. Being closed structures, there aren not end effects in Halbach spheres.

$$\vec{H} = \frac{4}{3} M_r ln(\frac{R2}{R1})\hat{y} \tag{8}$$

Although spheres can get higher and more uniform fields, they are more difficult to build and leave less space to its bore. Therefore, a Halbach cylinder will be used as the magnetic structure.

Halbach cylinders are a theoretical differential configuration that has to be approximated in a definite number of segments (Manlio G. Abele, 1993). Circular segments are more expensive than cubic magnets, so cubic magnets have been chosen to approximate the Halbach cylinder. Furthermore, they are easily stackable at four different magnetic orientation. The approximation of the Halbach cylinder made of cubic magnets is shown in Figure 3b.



(a)

(b)

Figure 3: (a) Theoretical implementation and (b) aproximaiton made of cubic.

Amongst permanent magnets, NdFeB generates the strongest magnetic fields in the smallest size and weight commercially available (Lucas et al., 2014). Therefore, NdFeB are going to be used. They are fragile and have a lower Curie temperature than other types of permanent magnets (supermagnete, 2018). That means that they can be demagnetize at lower temperatures than other material. Nevertheless, those temperatures are around 353 K, high enough for this application. Moreover, the magnets fragility is not relevant since they are going to be in a case which protect them tightly.

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