ORIGINAL PAPER

COMSOL SIMULATION OF ELECTROMAGNETIC FIELD REQUIRED FOR A MICROROBOT ACTUATION

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Abstract. *Starting from ancient age, physical phenomena have become more and more intriguing for humanity, and always evolutionary steps have been in strong connection with the idea of understanding their importance for a better life. Not once, the open minds were considered outrageous for their theories or the concepts and hypothesis regarding the reasons for which things are happening as it happens. One of the primary informations regarding to a force / phenomena which was capable to attract things date from 4000 years ago, when a Greek shepherd discovered a strange rock that somehow keept his shoes attracted to the ground. The name of the shepherd was Magnes and the lodestone from then is known as magnetite. In nowadays the magnets are being used in all sort of devices or machinery, in industry and even in medicine. On this considerent, the magnetic field that sustains the attraction force need to be in accordance with needs so; in Electronics this can be reach through coils and evenmore the magnitude of it can be adjusted to fits the requirements. This study proposes a simple design of a coil which can be used inside of electromagnetic actuation systems for controlling the motion of microrobots. In this matter, it is required to define for this electronic component the right characteristics (dimensions, number of turns etc.), and simulate its actual capabilities as an indivudal constitutive element of a system. The actuation force is very important for a precise displacement of a microrobot under the influence of electromagnetic fields. Thus, it been taked into considerations the importance of knowing the acting of it before manufacturing process, reason for what a simulation was required to be done for the right adjustments to occure. In the last decades, the systems based on electromagnetic actuation used different types of coils grouped in all sort of forms for a better performance.*

Keywords: *electromagnetic field, micromagnet, microrobot, actuation.*

1. INTRODUCTION

The coil represents a passive electric device that has two terminals (heads) and is used in electrical circuits to store energy in magnetic field or for magnetic field detection. The specific parameter of a coil is its inductance [1].

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The coil is made by winding a conductor (generally copper) on a core. This core may be ferromagnetic, case when the coil is having a high inductance, or may be non-ferromagnetic, or even absent (the core being air), case when the coil is having low inductance.

The electromagnetic field is practically a physical field produced around bodies (things) that are electrically charged and affects other electrically charged particles or other magnetic materials (paramagnetic, diamagnetic or ferromagnetic) [2]. The electromagnetic field propagates indefinitely into space, constituting one of the main forces of nature. The electromagnetic field which is propagating in space is called electromagnetic wave [3].

The electromagnetic wave propagation mechanism is based on the phenomenon of mutual generation of the electric field and the magnetic field. The force lines of the fields are located in mutually perpendicular planes, hence the respective vectors are mutually perpendicular.

The main characteristic of the coil is the inductance (measured in henry, H) which is a physical magnitude, equal to the ratio between the magnetic flux established by a current circuit passing through it and the current intensity [4]. A variation of the current produces a variation of magnetic flux which in turn produces electromotive force that is trying to resist to current variation [5]:

$$U = U_0 \sin \omega t = -L\frac{di}{dt} \tag{1}$$

By integration, with the initial condition I = 0 (for t = 0) is obtained:

$$I = \frac{U_0}{\omega L} sin\left(\omega t - \frac{\pi}{2}\right) + \frac{U_0}{\omega L} \tag{2}$$

The term $\frac{U_0}{\omega L}$ represents the instantaneous current intensity of the coil which quickly disappears from the circuit due to Joule-Lenz's energy loss. Noting $I_0 = \frac{U_0}{\omega L}$, the time variation of the circuit current is:

$$\boldsymbol{I = I_0\, sin\left(\omega t - \frac{\pi}{2}\right)} \tag{3}$$

The current through the coil is lagging with $\frac{\pi}{2}$, resulting the the inductive reactance expression $\omega L = X_L$.

By magnetic aspect, the ferromagnetic materials used in construction of a coil are divided into several categories:

- diamagnetic materials $\mu_r < 1$;
- paramagnetic materials $\mu_r > 1$;
- ferromagnetic materials $\mu_r >> 1$ [6];

where: μ_r – represents the relative magnetic permeability ($B = \mu_r \cdot \mu_0 \cdot H$); B – is magnetic induction, H - represent the intensity of magnetic field.

A basic characteristic of ferromagnetic materials consists in the dependence of magnetic induction B with the intensity of the magnetic field H. The dependence B = f(H) is called magnetization curve, the form of it being closer to an hysteresis cycle (Fig. 1).

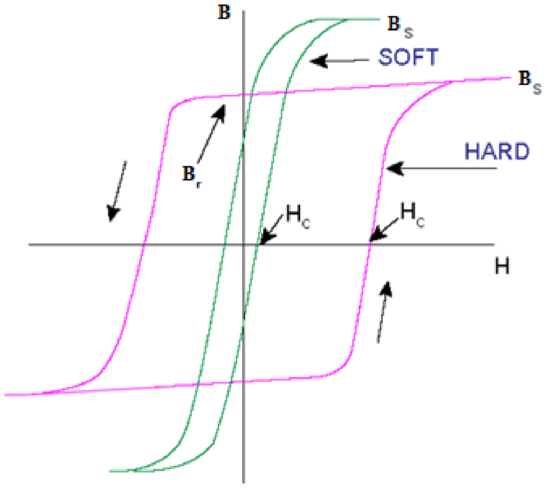


Figure 1. Hysteresis curve [7].

Optimal properties for ferromagnetic materials are:

- the relative magnetic permeability as higher as possible;
- induction to a higher saturation;
- specific losses as low as possible (through hysteresis and swirling currents) in the case of time-varying magnetic flux cores;
- manufacturing technology as cheap as possible;
- Adequate mechanical strength [8].

The materials used for constant flow cores are: laminated steel with thickness between 0.5 –50 mm, steel and cast iron, or forged steel. For variable flow cores are used silicon-tin (iron-carbon-silicon) sheets cold-rolled with non-oriented crystals, usually 0.5 mm thick, isolated with enamels or oxides or other soft composite materials [9]. Materials used for windings must have the lowest electric resistivity in order to reduce Joule losses.

$$P_j = RI^2 = (\rho \cdot L/S) \cdot I^2 \tag{4}$$

The most used materials are copper (Cu) and aluminum (Al). Alloys such as brass, bronze, tin, hydronali, silumini etc. are also used. For conductors subjected to important mechanical stresses, a higher degree of ecrusion is chosen. The winding conductors have a round or profiled shape and are used in isolated version (enamel, fiber textile etc.).

The main properties of Al and Cu used in coil windings are presented in Table 1:

Table 1. Main properties of aluminum and copper coils.

Coil	Electrical resistivity ρ [Ωm]	Density γ [kg/m^3]	Temperature coefficient α [°C^{-1}]	Accepted unitary effort for stretch to tear σ_{ar} [MPa]
Al	$3.1 \cdot 10^{-8}$	2700	$3.7 \cdot 10^{-3}$	70 ÷ 230
Cu	$1.8 \cdot 10^{-8}$	8890	$3.8 \cdot 10^{-3}$	210 ÷ 450

The resistivity varies with temperature, as follows:

$$\rho_\theta = \rho_{20}[1 + \alpha(\theta - 20)] \tag{5}$$

2. COIL DESIGN

Designing of the coil consists mainly in the calculation of all the elements that contributes to defining the constructive structure of it, the geometric shape and dimensions. Are taked into account also the technical and technological possibilities of its manufacture, starting from certain initial data and exploiting requirements. The characteristics of the coil (size, number of windings etc.) will determine, together with coil currents, the electromagnetic field values required for the movement of a micromagnet [10]. When designing the coils, it is intended that the space occupied by the coil to cover a surface, as little as possible. Thus, a coil with the following features has been designed:

- dimensions Lxlxh: 17x11x11 mm (Fig. 2);
- number of turns: 2190
- core diameter: 4 mm;
- core material: Fe;
- type of conductor: Cu;
- conductor diameter: 0.113 mm;
- resistance: 120 Ω;

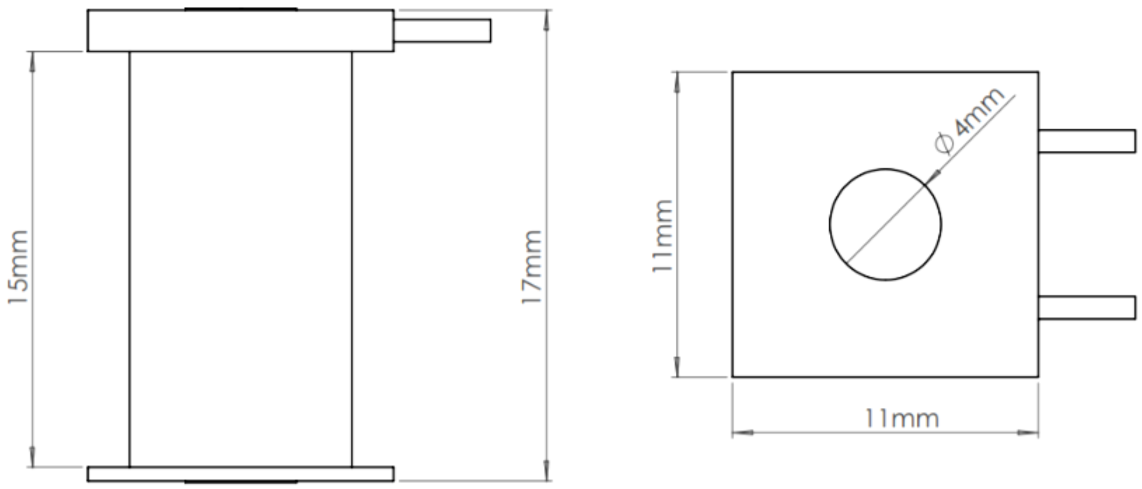


Figure 1. Coil dimensions.

3. ELECTROMAGNETIC FIELD SIMULATION FOR A MICROMAGNET ACTUATION

The simulation of the electromagnetic field used to actuate (octagonal plan displace) a micromagnet was performed using COMSOL Multiphysics development environment software. The simulation is intended to calculate the electromagnetic field generated by coils with characteristics described above, in the region of interest presented in Fig. 3.

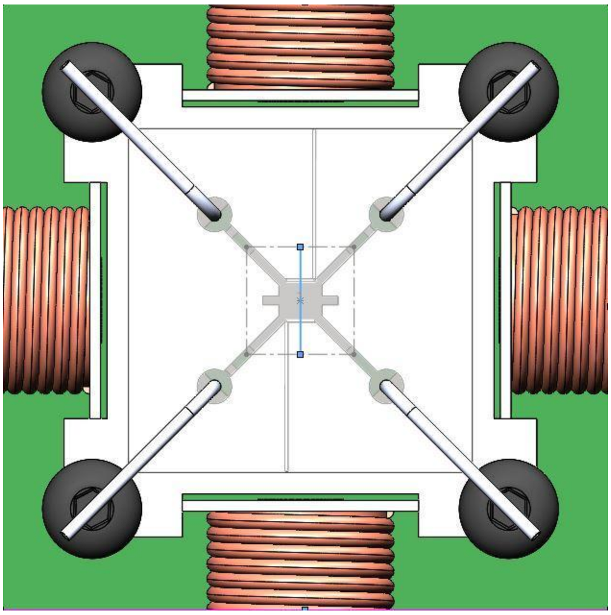


Figure 3. Region of interest of microrobotic system for wich was achieved the electromagnetic field simulation.

Fig. 4 shows the electromagnetic field obtained by simulation for such a coil by applying a voltage of 12V and a current of 110 mA.

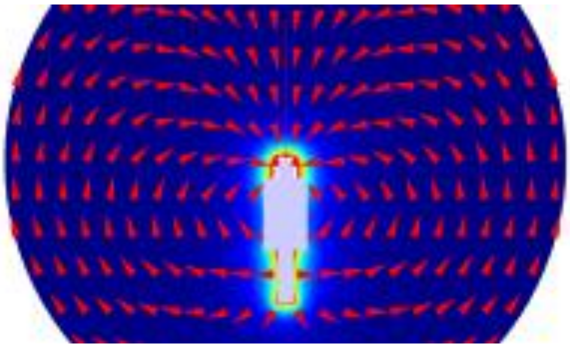
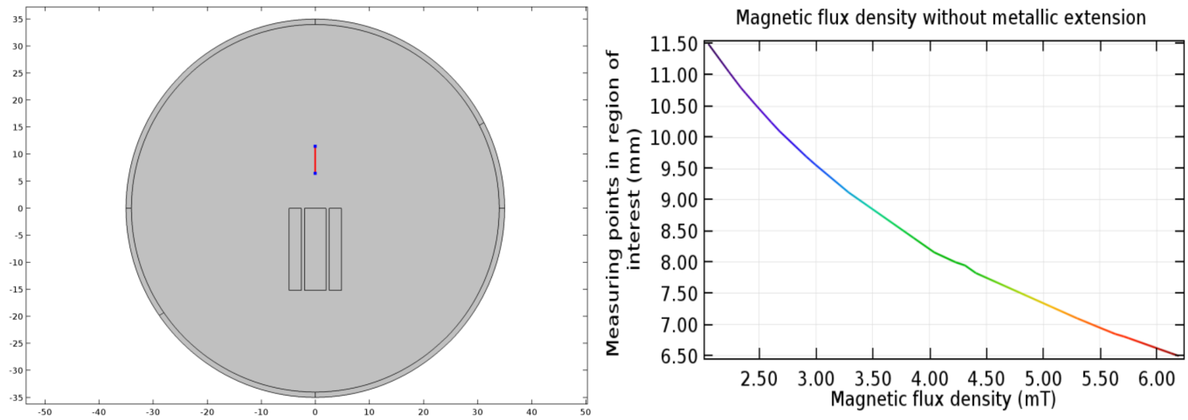


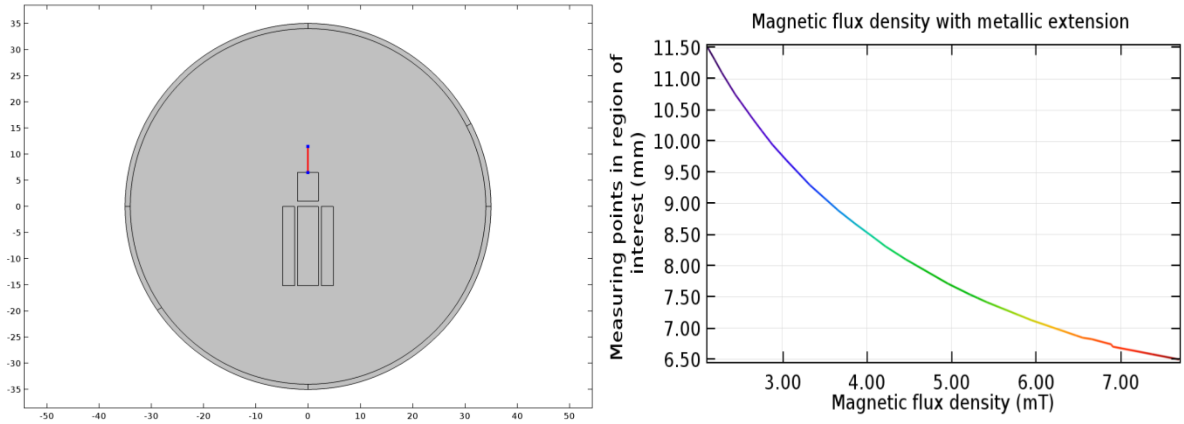
Figure 4. Finite element simulation of magnetic field created by a coil.

The simulation of electromagnetic field was accomplish for a coil with core, but also with an extension of it containing material addition (Fe), in order to increase the intensity of the electromagnetic field. The obtained data are presented in Figs. 5-6.



a. **b.**

Figure 5. Electromagnetic field simulation: a. electromagnetic field area studied in relation to coil position; b. intensity of the electromagnetic field for the coil without material addition.



a. b.

Figure 6. Electromagnetic field simulation; a. Electromagnetic field area, studied in relation with coil position; b. Magnetic flux density for the coil containing 5 mm material addition and having 1 mm distance between added material and coil core.

In the Fig. 5b is shown the dependence of magnetic flux density without metalic extension at different measuring points in the region of interest (ROI). It can be observed that the magnetic flux density in ROI is in the range of 2.08 to 6.11 mT. By adding a 5 mm metallic extension at 1 mm distance to the core (Fig. 6a), the magnetic flux density is reach 7.69 mT. On the both cases, the measurements were made at same parameters.

4. CONCLUSION

The purpose of this study was to obtain an accurate information regarding the aspects of adding metallic extension, in order to increase the magnetic flux density and control in region of interest a microrobotic agent with higher precission. COMSOL Multiphysics was used to establish the right parameters for further development of the microrobotic system. After simulations were completed it was demonstated that by adding metallic material, the magnetic flux density was increased by 25.86%.

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