Impact of the initial position of a plunger in a coil gun

C. Albert, N. Prouteau, V. Gies, and T. Soriano

Université de Toulon,
Avenue de l'Universit, 83130 La Garde, France `rct@univ-tln.fr`
Home page : http://rct.univ-tln.fr

Abstract. In this paper, a method for determining the movement of a plunger in a coil taking into account the variation of the coil inductance over the movement is presented. It uses a finite element software to calculate coil inductance values at each position of the plunger.

Taking into account all these parameters, this paper shows that the initial position of the plunger have a strong impact on the energy conversion from the coil to the plunger. A variation of 1cm in position leads to a variation of 27% of the energy transmitted.

Keywords: RoboCup Soccer, Middle-Size League, Multi-robot, Actuator Modeling

1 Theory : Principles of a Coilgun

1.1 Physical concept

Kicking systems at the RoboCup are relying on a well known phenomena called variable reluctance. Naturally, magnetic field in a magnetic circuit tends to be maximized. If a moving part allows that, this part will move in order to maximize the magnetic field or to minimize the reluctance of the magnetic circuit.

In our case, a large capacitor is discharged in a coil in order to produce a high current generating a magnetic field. In this field is located a mobile plunger (iron rod) sliding in a stainless steel tube : plunger is moved by the coil when the magnetic field is activated, in order to maximize it. That means the metal rod is attracted to the centre of the stainless steel tube and thus accelerated until it reaches this point, but it would be slowed down if the plunger goes over this point while the current in the coil is still present.

Current discharge on the coil could be characterized by a second order differential equation if the coil inductance was considered constant. However, this assertion is not true because movement of the plunger changes reluctance of the system as we will see later.

This paper propose to model the move of the plunger taking into account the variation of the inductance when iron rod slides forward in the coil.

1.2 Theory and equations

First, let's recall Hopkinson law :

$$\mathscr{F} = NI = R\Phi \tag{1}$$

With :

- $\mathscr{F}$: magnetomotive force (MMF and the unit is ampere-turn : At)
- N : number of turns of the coil
- I : intensity in the coil (A)
- R : reluctance (H^{-1})
- Φ : flux (Wb)

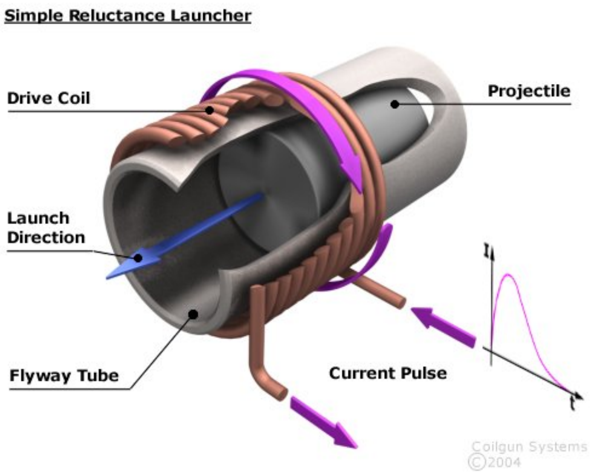

Fig. 1. Reluctance Launcher Diagram [1]

Therefore, magnetic flux is equal to :

$$\Phi = \frac{NI}{R} \tag{2}$$

The coil force is :

$$\vec{F} = \overrightarrow{grad(\vec{M} \cdot \vec{B})} \tag{3}$$

With :

$$\vec{M} = IS\vec{n}$$

It is not necessary to go deeper into the electromagnetic equations as the software called *FEMM 4.2*, programmed by D.C. Meeker, will be used for calculating the force and the inductance with the associated energy using a finite element model taking into account non-linearities such as saturations of the magnetic field.

We are briefly going to explain how the software is able to estimate these values in the next section.

Solving method Problem can be approximated as a finite time step one, that means the kicking system evolution can be considered as a succession of short time independent magneto-static problems. For each of these problems, following equations link magnetic field intensity B and magnetic excitation H:

$$\nabla \cdot B = 0 \tag{4}$$

$$\nabla \times H = J \tag{5}$$

We can also write this formula between B and H in a linear approach:

$$B = \mu H \tag{6}$$

or a more realistic non-linear approach :

$$B = \mu(B)H$$

The software FEMM tries to find a field that satisfies the linear approach and the flux density equation with the magnetic vector potential A defined as :

$$B = \nabla \times A \tag{7}$$

When this vector A have been found by the software considering the (6) and (8) equations with a conjugate gradient method, we can rewrite the formula on the flux intensity H like:

$$\nabla \times \left(\frac{1}{\mu(B)}\nabla \times A)\right) = J \tag{8}$$

With this equation, the software is able to calculate the vector A. With this vector, the software can now calculate the flux density and the field intensity that were missing in the calculus of the force.

Electrical theory Behaviour of the electrical circuit can be simulated by a charged capacitor and an inductor. However, this inductor is made with a very long copper wire so we can not ignore its resistance. This leads to the circuit 2:

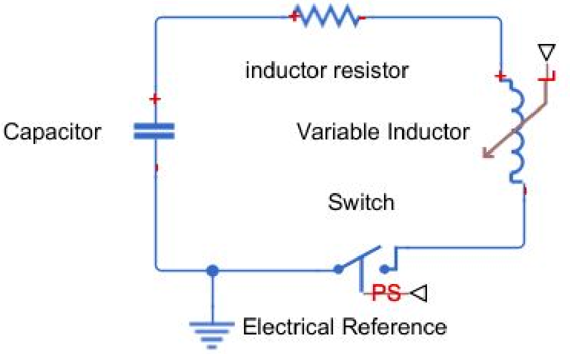

Fig. 2. Electric circuit

Applying Kirchhoff laws leads to :

$$U_{cap} = (R_L + R_{switch})i + L\frac{di}{dt} \tag{9}$$

With :

$$U_{cap} = \frac{1}{C} \times \int_0^t i(\tau)\,\mathrm{d}\tau$$

For a short amount of time, L can be considered as a constant, and circuit can simulated by :

$$\frac{1}{C} \times \int_0^t i(\tau)\,\mathrm{d}\tau = (R_L + R_{switch})i + L\frac{di}{dt} \tag{10}$$

2 Resolution of the differential equation

2.1 Evaluation of the inductance value depending on the plunger position

Solving the preceding differential equation by numerical methods requires to have the value of L for each position of the plunger. With this information, evolution of the current can be calculated, leading to know the displacement of the plunger, and then the iterated new value of L and so on...

To evaluate the evolution of L depending on the position of the plunger, we use a software called *FEMM 4.2* made by D.C. Meeker.

This software allows us to apply the equations above with our special geometry and gives us a lot of information that are really difficult to estimate precisely as the value of inductor and the force applied to the plunger over time and depending on where the plunger is in the coil. Indeed, to take into account the geometry of our different components, we need a finite element method and also conjugate gradient solver and this is what FEMM provide.

So, in this software we only need to describe the system environment, the materials, the current and the number of turns in the coil and with these information the software is able to gives us the force from the coil to the plunger and also the value of the inductor.

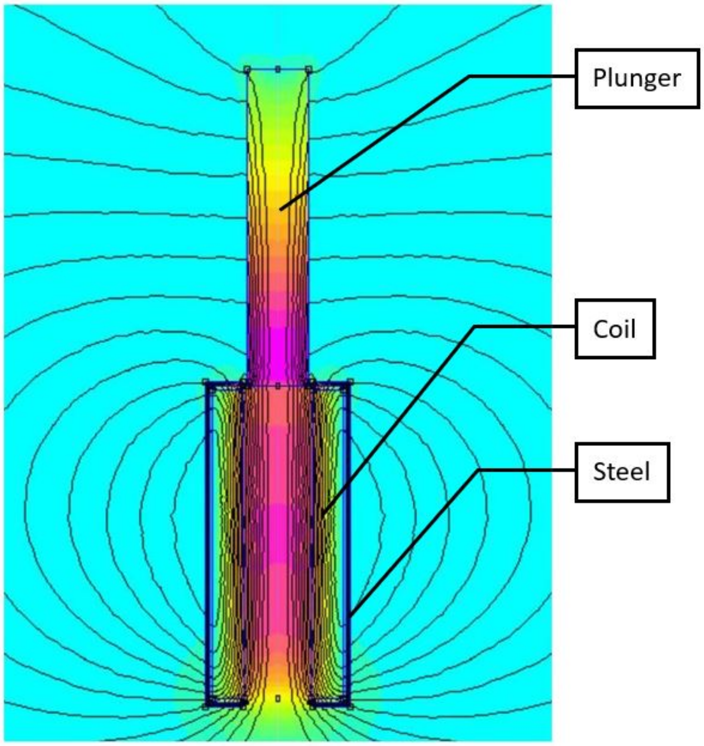

Fig. 3. Visualization of the magnetic field and the system design on FEMM

The software has been originally designed for studying static configurations, however our problem can be seen as a succession of static configurations. At each step, the current and the new position of the plunger can be calculated numerically using the instantaneous value of the inductance. Calculating this value for every configuration can be done using a Lua script linked to the finite elements software.

Fig. 4 shows the results of the computation of L inductance depending on the position of the plunger. We can notice that L value increases by more thant 50% during the 10cm move of the plunger. This confirms that L value can not be considered as a constant value.

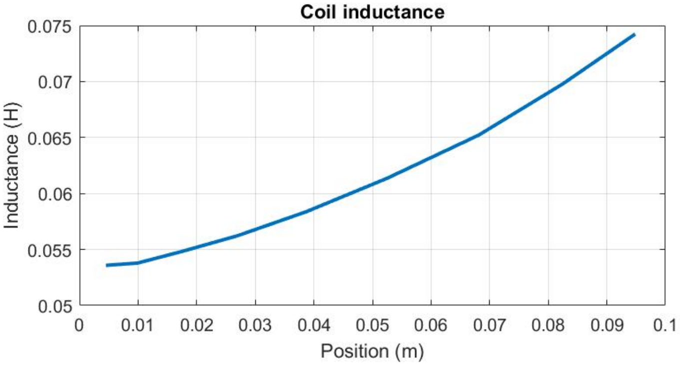

Fig. 4. The coil inductance as a function of plunger's position

2.2 Recursive formulation of the current differential equation

Having the inductance L evolution depending on the position of the plunger allows to solve numerically equation 10. Using Euler approximation leads to replace integration and derivations by :

$$\int_0^t i(\tau)\,\mathrm{d}\tau \approx i_n \times dt + \sum_{k=0}^{n-1}(i_k \times dt) \qquad \frac{di}{dt} \approx \frac{i_n - i_{n-1}}{dt}$$

This leads to recursive equation 11 :

$$i_n = \frac{V0 - \frac{1}{C} \times \sum_{k=0}^{n-1}(i_k \times dt) + L_{n-1} \times \frac{i_{n-1}}{dt}}{R + \frac{L_{n-1}}{dt} - dt} \tag{11}$$

Constants used in this equation are known or can be calculated. For example resistor value is equal to :

$$R = \rho_{copper}\frac{L_{wire}}{S_{wire}} \text{ with } L_{wire} = 2\pi N \times \left(R1 + \frac{R2 - R1}{2}\right)$$

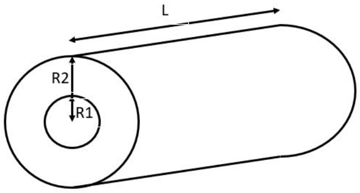

Fig. 5. Coil measurements

This leads to the following constants :

V_0	i_0	C	L_0	R	R1	R2	L	N
400 V	0 A	4700 μF	55 mH	5 Ω	1 cm	4 cm	10 cm	1200

2.3 Simulation results

In this section, recursive differential equation is solved numerically depending on the initial position of the plunger. This initial position has a strong impact on the movement : if the plunger is too much inside the stainless steel tube, variation of reluctance will smaller than the maximum possible, if the plunger is too much outside the stainless steel tube, current will have decreased too much when the plunger will enter the tube. Between that, their at least an optimal position for maximizing the top speed of the plunger.

Simulation with a plunger starting at $Z_0 = 0$, meaning that the plunger is at the border between the interior and the exterior of the coil, leads to the results shown at Fig. 6.

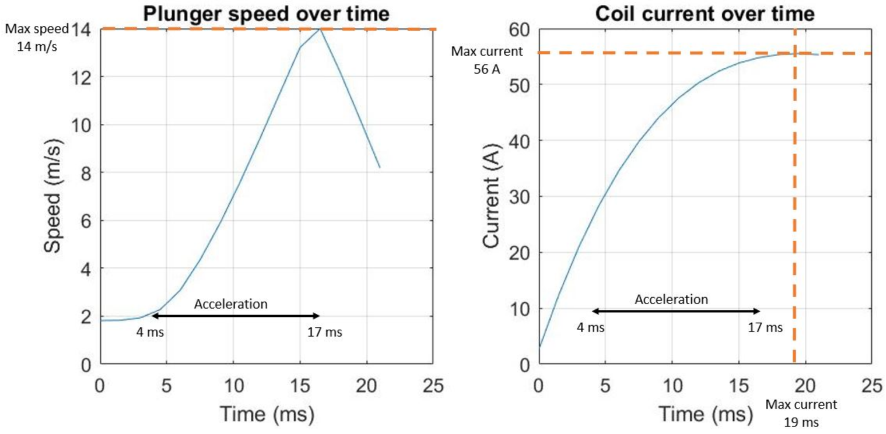

Fig. 6. Simulation with $Z_0 = 0mm$

Simulation with a plunger starting at $Z_0 = -10mm$, meaning that the plunger starts from outside the coil, leads to the results shown at Fig. 7.

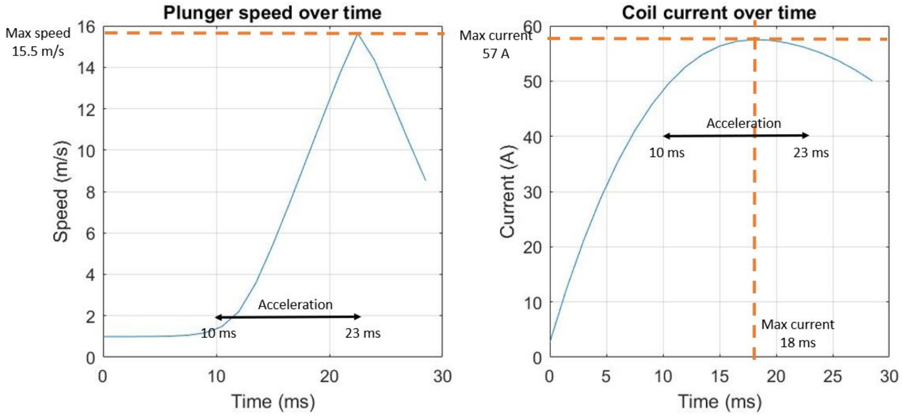

Fig. 7. Simulation with $Z_0 = -10mm$

Starting at $Z_0 = 0mm$ leads to a plunger acceleration from 4 to 17 ms with a maximum current obtained at $t = 19ms$ and a maximum speed of $14m.s^{-1}$ at $t = 16ms$ whereas the maximum current is reached at $t = 19ms$. In this case, current is growing to slowly compared with speed increase, leading to reach the maximal current when the plunger has already reached the centre of the coil and is decreasing its speed.
’

Starting at $Z_0 = -10mm$ leads to a plunger acceleration from 10 to 23 ms with a maximum current obtained at $t = 18ms$ and a maximum speed of $15.8m.s^{-1}$ at $t = 22ms$ whereas the maximum current is reached at $t = 18ms$. In this case, maximum current is obtained while the plunger is still accelerating, leading to a more efficient contribution of the current to the plunger acceleration. This leads to get a speed of $15.8m.s^{-1}$ instead of $14m.s^{-1}$ in the previous case. COnsidering kinetic energy is equal to $\frac{1}{2}mv^2$, energy transfer is 27% more efficient in the second case.

Conclusion

In this paper, we have proposed a method for determining the movement of a plunger in a coil taking into account the variation of the coil inductance over the movement. Instantaneous coil inductance values can be calculated by an existing finite element software.

Simulations have shown that taking into account all these parameters, the initial position of the plunger have a strong impact on the energy conversion from the coil to the plunger. A variation of 1cm in position leads to a variation of 27% of the energy transmitted.

In a further work, we will determine more precisely the ideal position of the plunger in order to maximize the output speed of the plunger and we will check that the results obtained are consistent with real experiments.

Another further work will lead us to evaluate the impact of using 2, 3 or 4 coils (each having a half, a third or a quarter of the total turns of the initial coil), triggered sequentially by software or using a position sensor instead of a single coil as shown in Fig. 8. This would lead to have successively a maximum current on each coil when the rod is optimally placed in the coil.

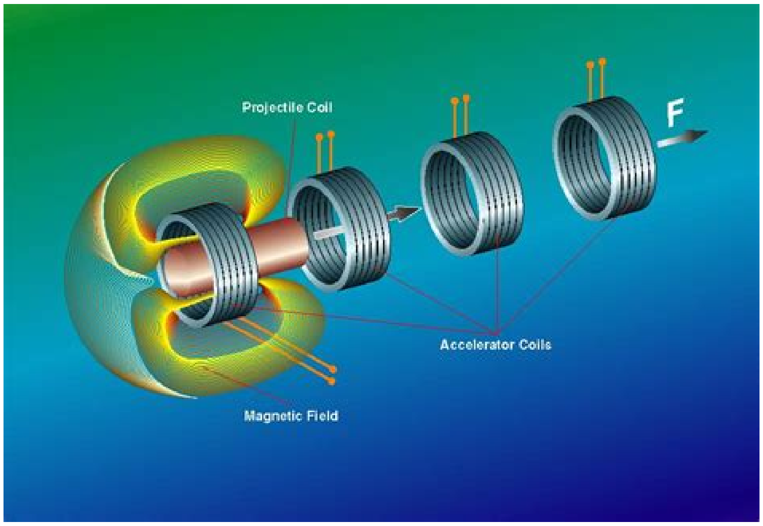

Fig. 8. 3D diagram of a system with multiple coils [2]

References

1. Author, U.: Simple reluctance launcher (18 July 2004)
2. Kang, Y.: Conceptual diagram of coilgun system (July 2008)