ISSN 2349-7815

International Journal of Recent Research in Electrical and Electronics Engineering (IJRREEE)
Vol. 3, Issue 3, pp: (37-43), Month: July - September 2016, Available at: www.paperpublications.org

Coilgun: Simulation and Analysis

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Abstract: **In this paper circuit for coilgun is simulated and analyzed using SIMULINK. Behavior of the magnetic field due to the current carrying coil is analyzed. Also, the effect on the coilgun performance for different weights of projectiles is investigated. The speed profile for different positions of the projectile is observed which is a critical parameter for coilgun operation. A comparison is drawn between the simulated and experimental results.**

Keywords: **Coilgun, damping, ferromagnetic, solenoid.**

I. INTRODUCTION

Chemical launching systems are widely popular and have high thrust and perform efficiently. But they are expensive; storing is difficult due to use of unstable chemical propellants and may contain toxic fuels. Coilgun is an electromagnetic launching system and is advantageous over existing chemical launch system as it's a fuel-free launching technology, eco-friendly (smoke free) and its range can easily be controlled by controlling the muzzle velocity through electrical current [1]. It also has higher repetition rate, silent and has low frictional losses. EMLs are mainly constructed as railguns or coilguns [2]. Construction of coilgun is simple but it is conceptually complex. Coilguns are further categorized depending upon their working principle, reluctance type and induction type coilgun. Research on the reluctance coilgun isn't as widespread in the literature as it is for the induction coilgun; however, there are some papers that provide a basic theoretical framework. In this paper the focus will remain on the reluctance type coilgun.

The potential applications of this concept can range from firing a bullet to launching big space payloads but the latter has of yet deemed impractical due to large stresses on the payloads [2].

II. COILGUN THEORY AND DESIGN

The reluctance type coilgun works on the principle of electromagnetism. In coilgun a fast rise time, high peak current pulse is passed through a solenoid which magnetizes the coil and creates a magnetic field [3]. This field attracts magnetically active (material with positive susceptibility) projectiles with high velocity and thus projectiles get accelerated along the axis of the solenoid (coil). The figure 1 below shows a reluctance type coilgun.

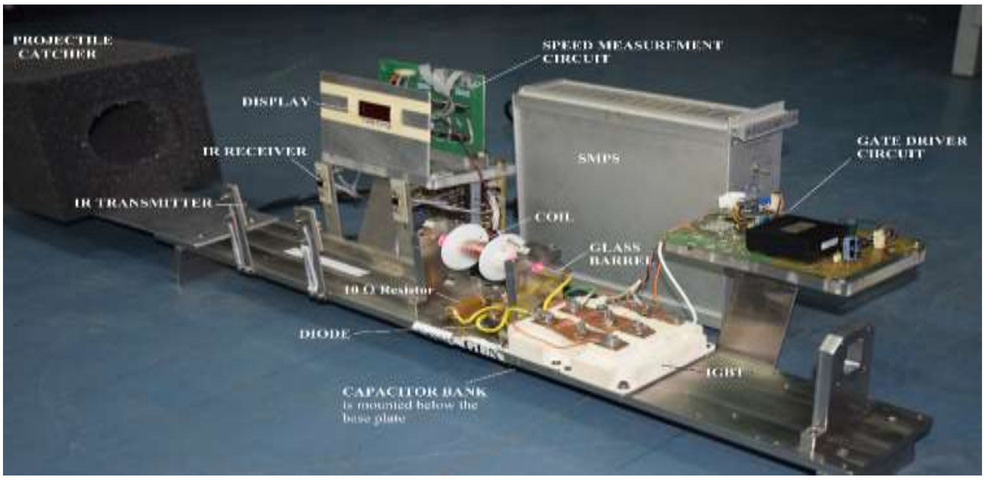

Fig.1. Photograph of initial prototype

ISSN 2349-7815

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The current pulse should be quenched before the projectile reaches its center otherwise the coil tries to draw the projectile in opposite direction this phenomenon is called suckback effect. Suckback action pulls the projectile back into the coil and decreases the speed. But if the current pulse is too short it will affect the efficiency of the system. Therefore, timing the current pulse is critical for the performance of the coilgun.

Fig. 2 shows the circuit diagram used for the coil gun. In the circuit a dc voltage supply charges the capacitor bank. After charging the capacitor is then discharged across the coil using IGBT as fast response high rating power switch.

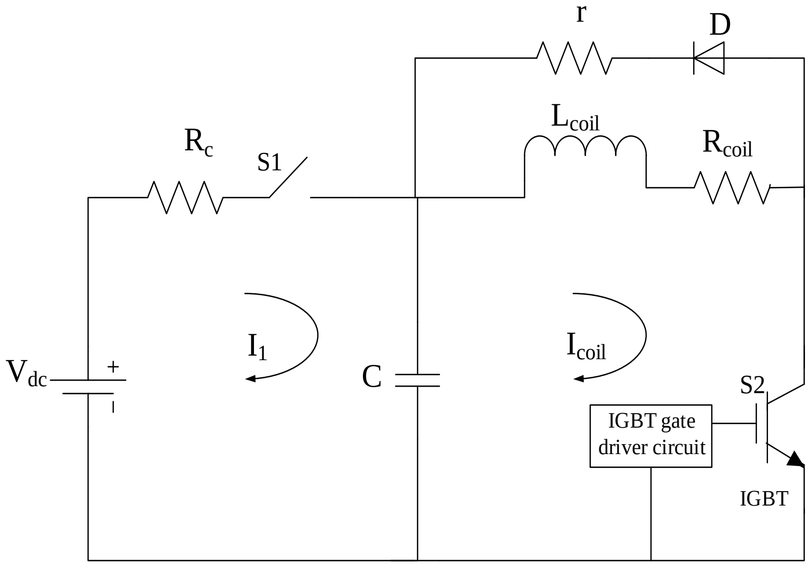

Fig.2. Circuit diagram of coilgun

When current flows through the coil it becomes an electromagnet and draws the projectile which is kept inside the coil along its axis. The current carrying coil pulls the projectile with a high speed such that it accelerates further into the coil due to initial inertia.

The current through the coil is given by

$$I_{coil}(S) = \frac{V_{dc}}{L(S^2+\frac{R_{coil}}{L}S+\frac{1}{LC})}$$

Comparing above equation with the standard second-order equation

$$Y(s) = \frac{k}{S^2 + 2\xi\omega_o S + \omega_o{}^2}$$

We get, natural frequency = $\omega_o = \frac{1}{\sqrt{LC}}$

Damping ratio = $\xi = \frac{R_{coil}}{2}\sqrt{\frac{C}{L}}$

Now depending on the value of ratio, the response of the circuit can be critical, under or over damped. The critical damping gives the quickest response but the peak is highest in case of under-damping with negative spikes. Peaks of opposite voltage can be eliminated using anti-parallel diode connected to a coil.

III. MAGNETIC FIELD AND FORCE DUE TO COIL

The magnetic field is generated when current flows through the coil. The magnetic field density on the axis of the coil can be expressed by the following equation for a thin shell finite solenoid at a point x from the center of the coil.

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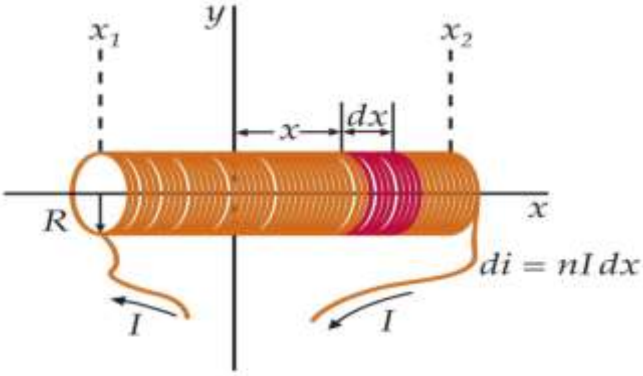

Fig.3. Finite length solenoid

$$B_x = \frac{\mu_0 nI}{2}\left(\frac{x - x_1}{\sqrt{(x - x_1)^2 + R^2}} - \frac{x - x_2}{\sqrt{(x - x_2)^2 + R^2}}\right)$$

Vertical components of the magnetic field cancel out each other i.e. $B_{radial} = B_{y.}$ Where

n = no. of turns per unit length, I = current through coil, R = radius of the coil

The magnetic field is plotted using MATLAB and it represents the variation of magnetic field with respect to the axial length of the coil as shown in Fig. 3. Magnetic field is maximum at the center of the coil and reduces to almost half of its value at the edge of the solenoid.

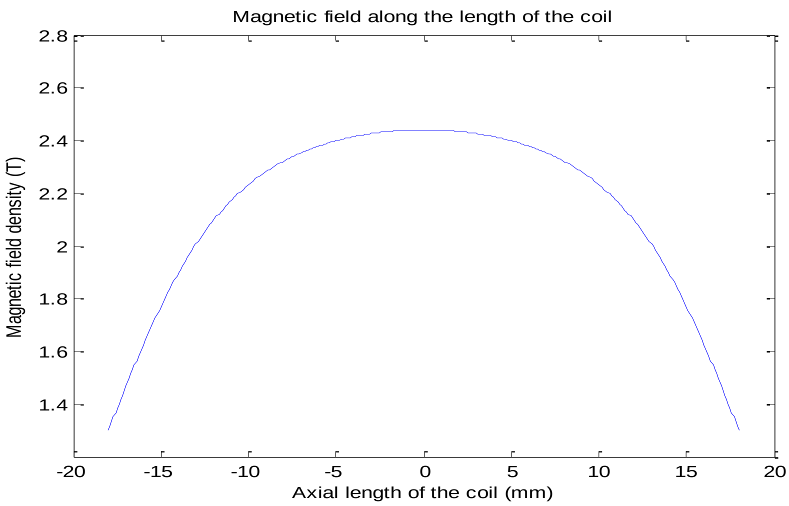

Fig.3. Magnetic field of the coil obtained using MATLAB

For an empty solenoid, the energy of magnetic field within it is given by

E (empty) = Volume x Magnetic energy density

= Volume x $B^2/2\mu_0$

When projectile is placed inside it, permeability of the material has to be considered.

Therefore, E (with projectile) = volume x $(B^2/2\mu_0)$ x μ_r

For a magnetic body in a magnetic field, assuming 100% conversion efficiency, the energy of the magnetic body is the difference between the energy values for empty and with projectile. Force exerted on the projectile is given by

Force = Change in energy / distance moved by the projectile inside the coil

= ΔE / L

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$= \pi R^2B^2/2\mu_0 * \mu_r\text{-}1$

The muzzle velocity of the projectile can be calculated by equating the change in energy of the field with the resultant kinetic energy of the projectile [3].

$$\frac{1}{2}mv^2 = \Delta E$$

Therefore, velocity $v = \sqrt{\frac{2\Delta u}{m}}$

Note: For above calculations the conversion efficiency is 100% also above equations doesn't consider variation in inductance as the slug enters; also many other simplifying assumptions overestimate the value of force and speed to a great degree. A conservative guess at coilgun efficiency is 1% and in a highly tuned coilgun, it might reach 2 % [4]. Furthermore, it ignores the effect of suck-back. This too, will overestimate the exit velocity and impair the accuracy of the model.

Force applied by a solenoid can also be given by the formula [5]

$$\mathrm{F} = \frac{1}{2}\mathrm{I}^2\frac{\mathrm{dL}}{\mathrm{dx}}$$

For measurement of speed Light-Gate method is used which gives much better accuracy.

IV. CIRCUIT SIMULATION AND EXPERIMENTAL RESULTS

When projectile enters in the vicinity of the coil; due to increase in the permeability of the medium inductance increases and when the projectile moves out of coil inductance decreases. From the Fig. 4 it can be inferred that the coil inductance is maximum at the center since the flux linkage is maximum at that position.

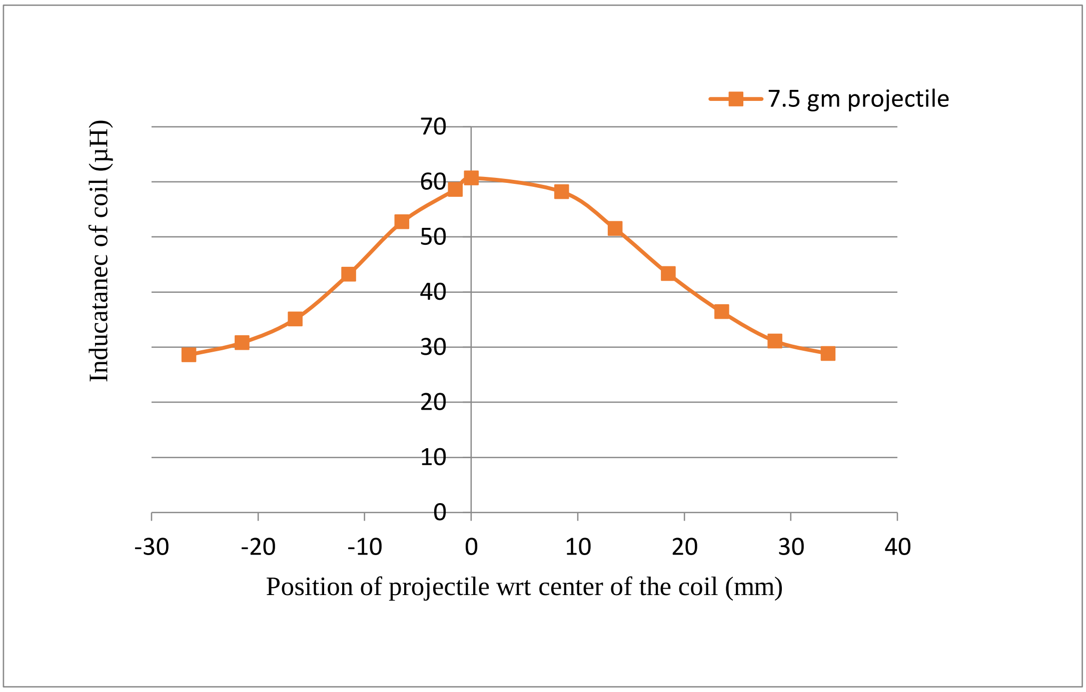

Fig.5. Inductance variation of the coil on insertion of projectile

The coilgun circuit is simulated in MATLAB in order to analyse the response for different parametric values. The figure below represents SIMULINK model of coilgun circuit.

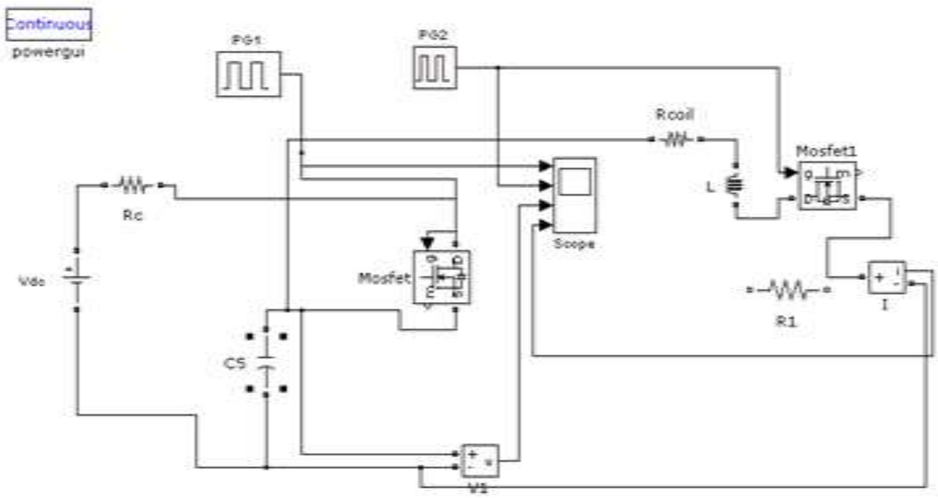

Fig.6. MATLAB simulation of coilgun circuit

The graph in Fig.6 is obtained from MATLAB simulation for coilgun circuit for fixed value of R, L & C. The actual current waveform obtained on oscilloscope for same parameter values is shown below in Fig. 7.

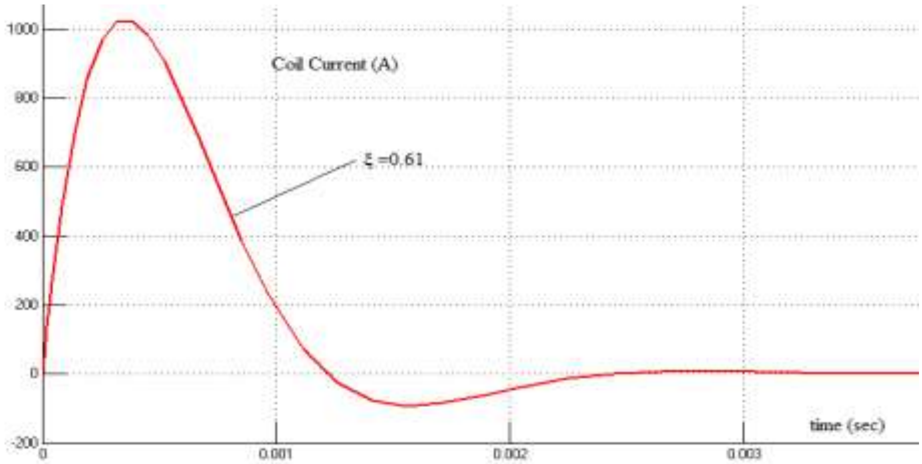

Fig.7. Simulated current waveform

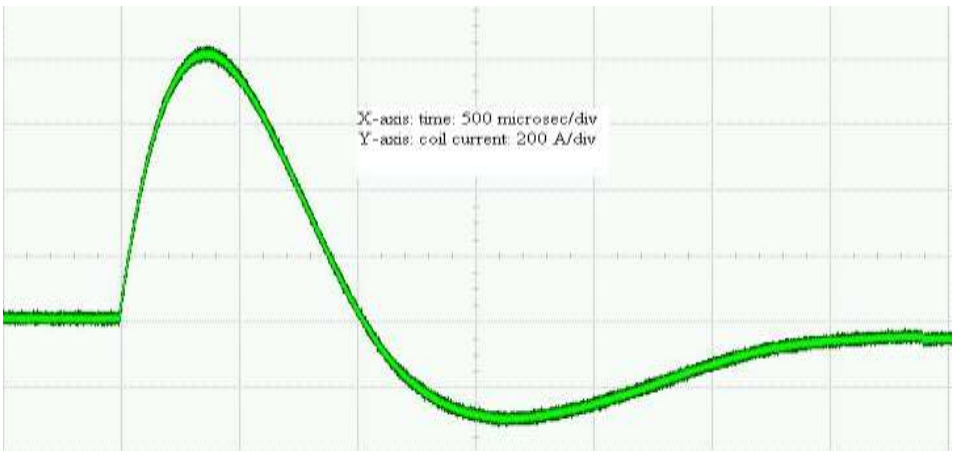

Fig.8. Actual waveform of coil current

ISSN 2349-7815

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On comapring the simulaed and actual current pulse both are found to have underdamped response for given parametric values. The difference in experimental coil current is due to variation in coil inductance on insertion of projectile which cannot be accounted for in MATLAB. The other factors responsible are skin effect, proximity effect etc. As mentioned earlier coilgun is sensitive to even milliohms of resistance. Therefore, the actual current waveform cannot match up exactly with the simulated one.

In the next experiment speed is measured for three different projectiles of 1.5 gm, 2.7 gm and 5.1 gm using Light-Gate method. Fig.9 shows the variation in speed of the projectile versus position of projectile with respect to center of the coil. The speed is maximum where change in inductance is highest since at that point coil pulls the projectile with maximum force.

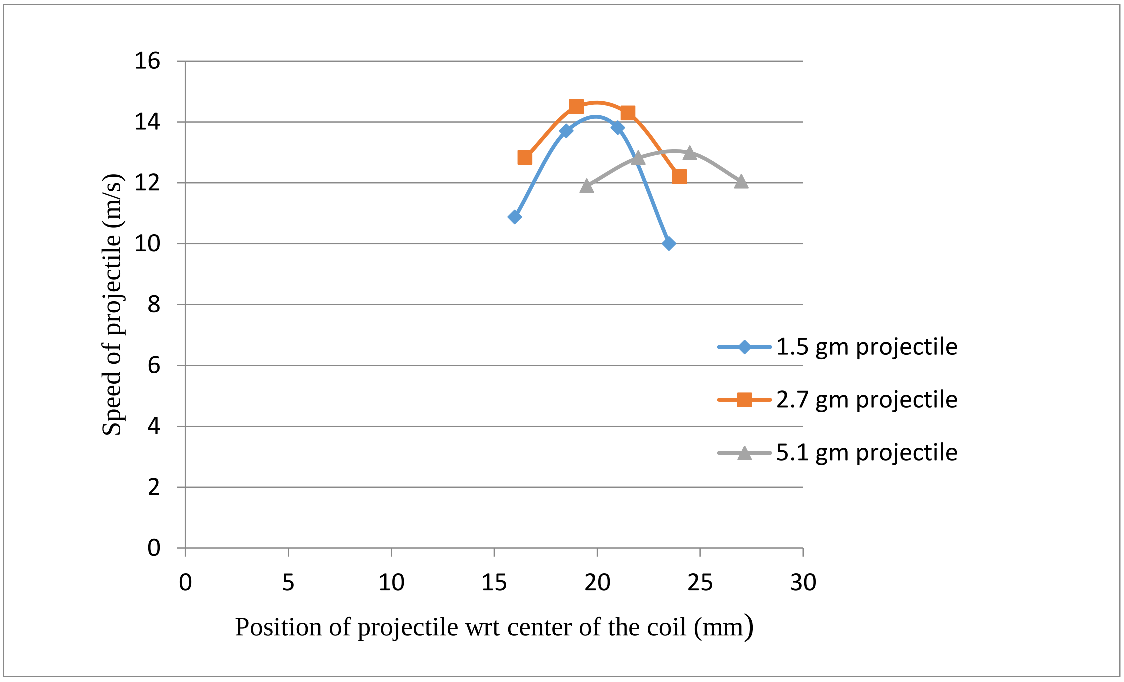

Fig.9. Speed vs. Position of projectile

The speed of the projectile varies with the position of projectile. When projectile is kept near the edge of the coil it's get pulled towards the coil. If the projectile is kept beyond the center of the projectile it is attracted in the opposite direction therefore the position of the projectile with respect to coil is a critical parameter to obtain better speeds.
This shows that for obtaining maximum speed the projectile should be long enough and should snugly fit inside the barrel for maximum flux linkage but not too heavy as to decrease the speed. The range of the coilgun can be scaled up by optimizing the electrical parameters of the circuit also to increase the speed of the projectile more stages of the coils are added which are triggered sequentially.

V. CONCLUSION

This paper concludes that the position of projectile is very critical to get the maximum speed for the given weight of projectile and the projectile should be designed such that magnetic field linkage should be maximum but weight should be minimum. The comparison between simulated and experimental data is made successfully. To further increase the speed without sacrificing the efficiency; building a multi-stage coilgun is the most logical approach.

VI. ACKNOWLEDGMENT

The work was carried out in Raja Ramanna Centre for Advanced Technology, Indore. I would like to thank Mr. Praveen K. Agrawal (SO/F) for his constant support and guidance. Also, I am thankful to Mr. S. V. Nakhe (Head, LSED, RRCAT Indore) for giving me the opportunity to work in his division. I would also like to acknowledge Mr. D.V.S. Raju, Mr. Jagdish Kumar for their help and guidance.

ISSN 2349-7815

International Journal of Recent Research in Electrical and Electronics Engineering (IJRREEE)
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