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Literature Review of Various Technologies Used for Electromagnetic Launcher

V.V. Khatavkar[1], R.S. Borse[2], S.S. Wani [3]

[1] *Senior Professor, Department of Electrical Engineering, PES's, Modern College of Engineering Pune, India*

[23] *Student, Department of Electrical Engineering, PES's, Modern College of Engineering Pune, India*

***Abstract*— The electromagnetic coil launcher is a new type of induction launcher that can generate a radial magnetic field. This type of electromagnetic coil launcher replaces conventional rail-gun launcher technology as it has some inherent problems like less acceleration force, less muzzle velocity, etc. and some other technical limitations. The railgun & coil gun launchers were upgraded to multipole field electromagnetic launchers. This paper is based on the theoretical review of an multipole field electromagnetic launcher various connection patterns their structural diagrams, electromagnetic technologies, and their various configuration are also discussed in this paper. Also, it represents results, basic formulae for inductance and resistance calculations for electromagnetic launchers are also briefed.**

***Keywords*— coil-gun launcher, multipole field electromagnetic Launch (MFEL), eddy current, octupole, electromagnetic force.**

1. INTRODUCTION

The Electromagnetic launcher is based on the principle of interaction between the eddy current and magnetic field and the electromagnetic force to propel the object. This electromagnetic energy and the accelerating force are used to propel the objects forward and accelerate the materials. The electrical energy is turned into kinetic energy which is to move the objects ahead [1]. The Multipole field electromagnetic launcher consists of pancake winding and the multipole electromagnetic field configuration to propel the projectile, it proved that by making use of octa-pole magnet provided a high accelerating force and a good muzzle velocity [2]. The use of an non-conductive magnetic core increased the conversion efficiency and decrease in the resistance losses due to increase inductance it improved the performance of the launcher [3]. The twisted multipole field electromagnetic launcher improved the fly stability and provided large thrust and high-speed launch [4]. The different connection of a coil pattern provides the comparative analysis regarding the eddy current distribution and the magnetic field in various, configurations [5]. The electromagnetic catapult circuit consists of excitation and acceleration coils, projectile or object, a capacitor charging circuit, capacitor bank, triggering the switch.

2. DIFFERENT CONFIGURATIONS OF THE ELECTROMAGNETIC LAUNCHER

A. Multipole Field Electromagnetic Launcher

The electromagnetic launcher uses winding in the shape of a pancake for the catapult. The capacitor discharges current into the coil all the coils are charged simultaneously. There is an interaction between the induced current and the magnetic field which provide repulsive forces to propel a projectile. The charging of coils is being carried out by capacitors. As the coils are placed in the closed proximity to each other eddy current are produced, the produced magnetic field interacts with eddy currents and creates a huge propulsion force causing a projectile to move at high speed. The use of a multipole magnet produces a radial magnetic field. Whereas the use of multiple coils produces loop current around projectile and the radial magnetic field is produced due to interaction between eddy currents and magnetic field.

"As per the law of electromagnetic induction - magnetic field interacts with the eddy current and produces the magnetic force. This force pushes the projectile thus giving it an initial speed. The eddy-current element obtains the electromagnetic force. The direction of the magnetic field is slant across the underside of the projectile, so the direction of the electromagnetic force is slant" [2].

$$d\vec{F} = I d\vec{l} \times \vec{B} \qquad (1)$$

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The capacitor discharges in the Driving coil where: -

Vc – Charge voltage of a capacitor

D – Diode

Ld. – Inductance

Rd - Driving coil Resistance

Lp – Projectile self-inductance

Rp – Resistance of projectile

Mdp - Mutual inductance between Projectile and Driving coil

The discharging of capacitor takes place into the drive coil when the lever of switch is closed then closed-circuit equation is given by

$$R_d i_d + L_d \frac{di_d}{dt} + M_{dp} \frac{di_p}{dt} + i_p \frac{dM_{dp}}{dt} - V_{c0} - \frac{1}{C}\int_0^{t_{up}} i_d \, dt = 0 \quad (2)$$

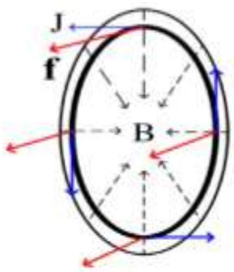

Fig. 1 -- Forces acting on the multipole field coil current

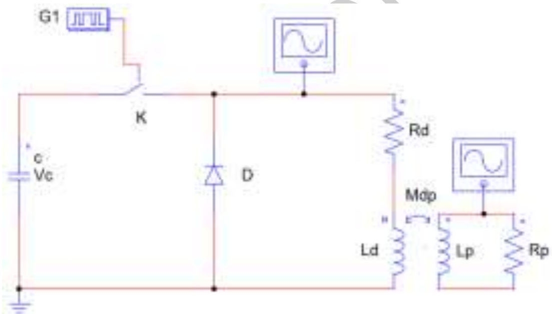

Fig. 2 - Multipole field electromagnetic launcher equivalent circuit diagram

When the capacitor is completely discharged into the coil the equation changes to

$$R_d i_d + L_d \frac{di_d}{dt} + M_{dp} \frac{di_p}{dt} + i_p \frac{dM_{dp}}{dt} = 0 \quad (3)$$

The simulation results indicate that it provides a high muzzle speed and greater acceleration force. Figure [3][4]

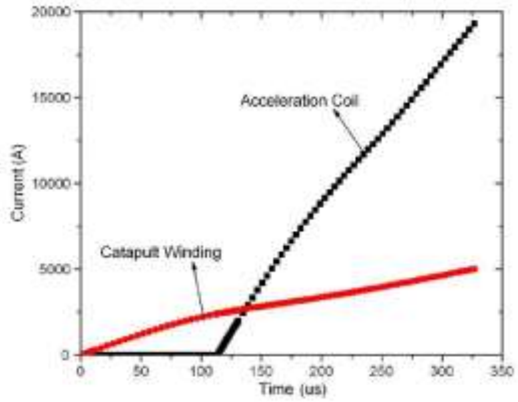

Fig. 3 – Graphical representation of acceleration coil and catapult coil current

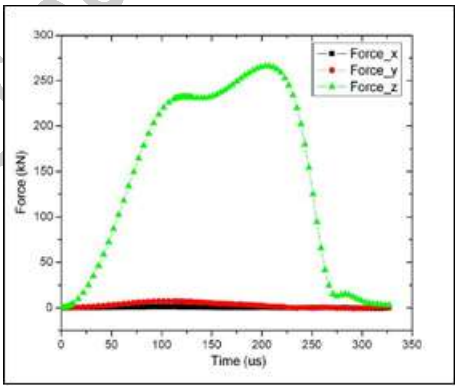

Fig. 4 – Graphical representation of electromagnetic force on projectile

It provided a better accelerating force and a good conversion efficiency compared to the traditional railguns [2].

B. Three-Stage Twisty Octapole Multipole Field electromagnetic launcher

In previous model of multipole field electromagnetic launcher, the placement of coils was exactly one above the other [1] but in twisty multipole field electromagnetic launcher the coils of every stage are twisted at a specific angle to the coils placed in previous stage as shown in the fig below

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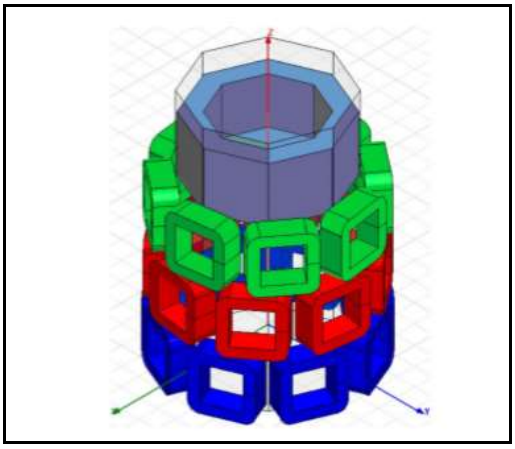

Fig. 5 – Three stage twisty multipole electromagnetic field launcher

Due to this twisty coil placement configuration, it resulted in a twisty electromagnetic field and improving the flying stability of the projectile as it moved with the axial position of the electromagnetic launcher and because of this magnetic field interaction with the closed-loop eddy current of the projectile, it produces a greater axial component of electromagnetic force and is utilized to accelerate the projectile. The eddy current is induced on the projectile, the skin effect of eddy current is also taken into consideration and given by –

$$\delta = \sqrt{\frac{2}{(\omega\sigma\mu_0\mu_r)}} \quad (4)$$

The octupole coil of the next stage is placed at a twisted angle of 15^0 and capacitors are fired in a sequence determined by the discharge position. "Numeric simulation results of the three-stage twisty octa-pole field electromagnetic launcher indicate that the magnetic torque of rotational motion is large and the transverse displacement of the projectile is very small" [4].

C. Different coil connection pattern-based launcher.

In conventional railgun launchers or the electromagnetic launchers, the flux produced by the coils have the same direction. By making use of various connection patterns MFEL can produce various magnetic field configurations and accordingly the inductance of the launcher is changed. Therefore, it is necessary to find certain optimal connection pattern.

The interaction between the eddy current and the radial magnetic field results into large axial accelerating force. The different coil connection patterns set up the inward and outward magnetic field due to which flux linkage is stronger.

The relation between electromagnetic flux and the inductance is given by the following equation[5].

$$W_m = \frac{1}{2}L_p i_p^2 + \frac{1}{2}L_d i_d^2 + M i_p i_d \quad (5)$$

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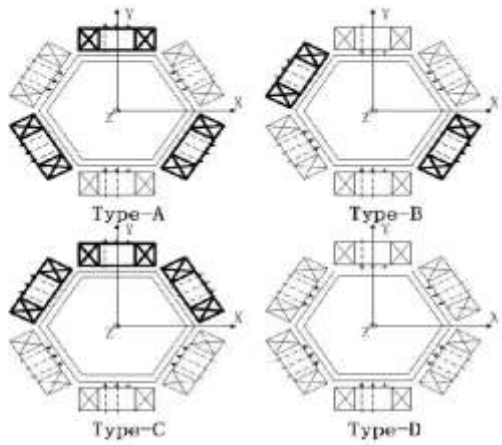

Fig. 6 – Top view of four types of driving coil setup

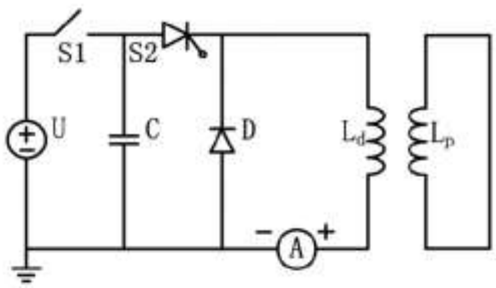

Fig. 7 – Six pole schematic diagram of driving coil circuit

The equation is of circuit is given by Kirchhoff's law as

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$$R_d i_d + L_d \frac{di_d}{dt} + M_{dp} \frac{di_p}{dt} + i_p \frac{dM}{dt} = U_C \quad (6)$$

The capacitor is discharged into the driving coil, the energy stored in the driving coil is transformed and it is converted into kinetic energy and experienced on the projectile making it move forward. Without any collisions with is neighboring driving coils, the projectile is capable to fly vertically upwards. “The neighboring driving coils have currents in the opposite direction and it produces a stronger magnetic field and more uniform eddy current distribution.

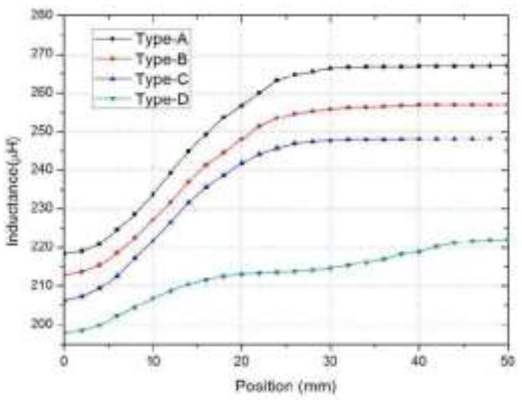

Fig. 8 – Inductance verse position along the axis

The thrust force is represented as

$$F = \frac{dW_m}{d_x} = \frac{dM}{dx} i_p i_d \quad (7)$$

The Type-A connection pattern as shown in fig [6] whose current direction in adjacent driving coils is opposite, and it is observed that the propulsion efficiency of the electromagnetic launcher increases as the initial voltage of the capacitor increases” [5].

D. Electromagnetic launcher with double armature configuration

Single-stage six-pole driving coils set up are shown in Fig. 9 (a). The conventional multipole field electromagnetic launcher consists of single armature placed inside of MFEL, and double armature coil are shown in Fig. (b)

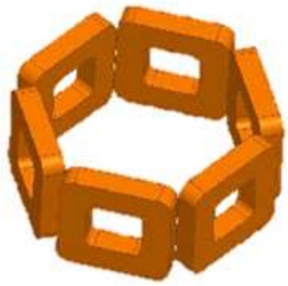

Fig. 9 (a) – Single-stage six-pole driving coils

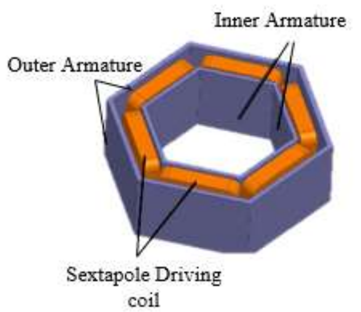

Fig. (b) – inner & outer armature

The charging of driving coils will setup the electromagnetic field between the outer and the inner regions of the driving coils. The conventional electromagnetic launcher makes use of a single driving coil setup. In double armature coil setup, the driving coils are placed inside and outside, this makes use of both the outer and inner magnetic field resulting in better energy conversation from electric energy to kinetic energy.

The double armature configuration for electromagnetic launcher, characteristics are determined by the uniform distance between the six driving coils and the mutual influence between the outer and inner armatures.

The experimental setup indicated that by applying a maximum voltage upto 2kv the results obtained were having high muzzle velocity, high energy efficiency, high propulsion force. Due to the opposite connection pattern the currents of the neighboring driving coils are in opposite direction.

The following two table shows the comparison of experimental results for both the single armature and the double armature launch [6].

Initial charged voltage	Single inner armature		Single outer armature	
	Muzzle velocity	η (%)	Muzzle velocity	η (%)
1 kV	1.75 m/s	0.0483	1.56 m/s	0.0538
1.5 kV	2.97 m/s	0.0619	2.62 m/s	0.0674
2 kV	4.20 m/s	0.0696	4.32 m/s	0.1031

Table 1 – Experimental results on single armature launch

Initial charged voltage	inner armature		outer armature		Total η (%)
	Muzzle velocity	η (%)	Muzzle velocity	η (%)	
1 kV	1.08 m/s	0.0184	1.40 m/s	0.0433	0.0617
1.5 kV	2.83 m/s	0.0562	2.91 m/s	0.0832	0.1394
2 kV	4.02 m/s	0.0637	4.43 m/s	0.1084	0.1721

Table 2 – Experimental results on double armature launch

E. Core type multipole field electromagnetic launcher

In core type launcher the coils are placed inside the fixed structure made up of conducting material which leads to a decrease in the reluctance of the projectile and an increase in the flux linkage on the projectile.

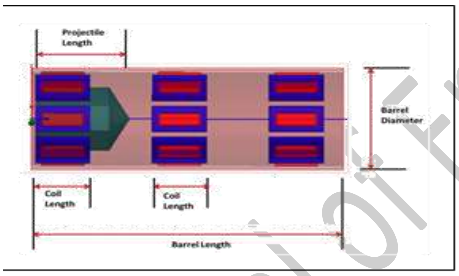

Fig. 10 – Geometrical configurations of Cored type MFEML

The magnetic properties are based upon the electromagnetic thrust, coil input, phase current, current density, coil inductance, coil resistance, coil reactance, muzzle velocity, acceleration; and the material parameters are depended upon the current density, permeability of free space, permeability of a material, volume resistivity of copper volume resistivity of aluminum. From the electrical equivalent circuit diagram and Kirchhoff's voltage law can be given as-

$$V(t) = R_a + L\frac{dl}{dt} + \frac{1}{c}idt \qquad (8)$$

The simulation of core type launcher indicated that there is increase in flux linkage as well as increase in force and velocity in minimum time.

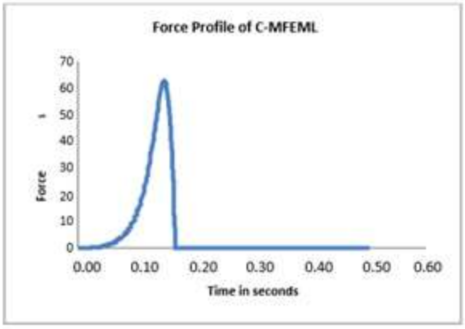

Fig. 12 – Force profile of C-MFEML

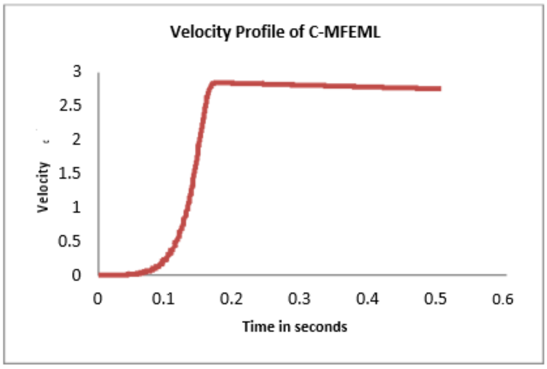

Fig. 13 – Velocity profile of C-MFEML

The use of core type multipole field electromagnetic launcher analysis resulted that making use of M15 Steel core with a flux density of 1.10644 Tesla produced a large amount of force to propel the projectile compared to coreless multipole field electromagnetic launcher [7].

F. Single-stage double-layer multipole field electromagnetic launcher

The traditional MFEL consists a gap between the driving coils and sleeve armature which results in a decrease in the magnetic coupling and the conversion efficiency. In MFEL with double layer and six saddle-shaped coils are placed between the inner and outer layer with relative torsion angle resulted in more stronger electro-magnetic field and uniform distribution of eddy currents. When the pulsed current flows in the driving coils, magnetic fields are generated by the coils, and eddy current is induced on the armature, which is an aluminum alloy sleeve. The magnetic flux distribution (B) and eddy current loops (J) are shown in Fig.14 (a) and Fig. 14 (b).

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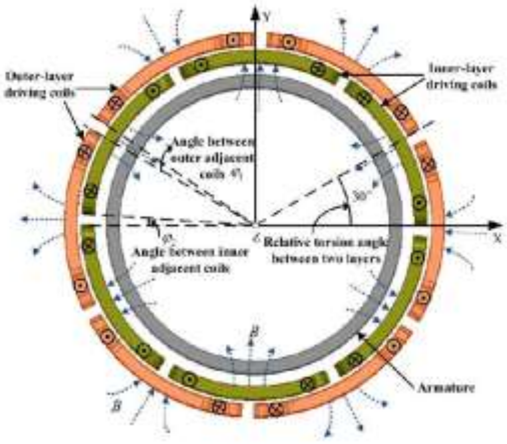

Fig. 14 (a) – Top view of single layer double Multifield electromagnetic launcher

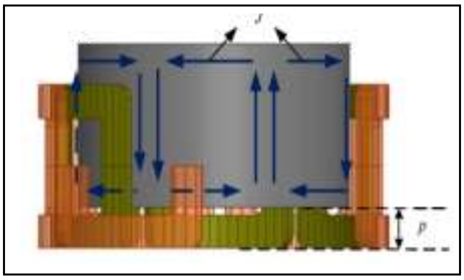

Fig. 14(b) – Side view of single layer double Multifield electromagnetic launcher.

The tangential rotational force and the axial propulsion force are generated because of the integrated effect of the eddy current loop and the electromagnetic field causes the acceleration with rotational motion of the armature along the axial direction This type electromagnetic launcher can achieve improved rotational and linear performance at the high voltage. The experimental results are shown below

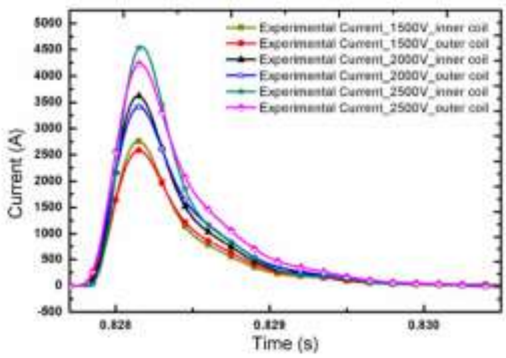

Fig 15 - Experimental Curves of the currents of Single-stage double-layer multipole field electromagnetic launcher

The results indicate that high linear muzzle velocity compare to traditional launchers. "As the kinetic energy of the armature is proportional to the initial energy storage the rotational and linear velocities increases with the increase of voltage" [8].

G. Electromagnetic Launch by linear Quadrupole Field

The generation of the electromagnetic field from all the four sides is termed as a quadrupole. This launch field is based on DC quadrupole field where huge actuating force is obtained by DC magnetic field there is no pulse power required, DC power is supplied to the projectile and both launch tube and highspeed enables the launch of a high-speed projectile and resistive heat losses are negligible, proposed launcher provides the region to load sensitive devices without magnetic shielding. The rupole magnetic field launcher can provide a larger thrust than traditional railguns. This kind of launcher is capable to launch massive projectile, which also contains sensitive devices [9].

H. An electromagnetic rail launcher by rupole electromagnetic field

In rupole electromagnetic field consists of four rods placed in the square magnetic field are shown in Fig. 13, it provides a larger thrust for the heavy projectile. The magnetic field generated by rail current interacts with armature current and moves the armature field. The armature structure influences the distribution of the electromagnetic field and the armature current The interaction between the armature current and the magnetic field results in to large thrust. The Lorentz force act on the projectile. Rupole magnetic field launcher is capable to provide huge thrust than a conventional railgun [10].

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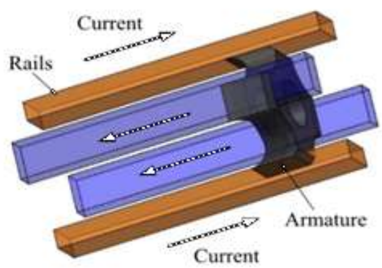

Fig. 16 - Rail gun

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3. LAWS AND CALCULATION

According to the Lorentz force law, the force is a combination of magnetic and electric force on point charges due to the electromagnetic fields [8][10].

$$F = B\,I\,L \qquad (9)$$

Where,
B = magnetic field
I = current through the armature
L = length of coil
e is an interaction between the magnetic field B and the current density J of the projectile in the space in electromagnetic launcher [4].

$$J = \nabla \times \frac{B}{\mu} \qquad (10)$$

The Projectile Experiences a force generated by Lorentz force
As per the conversion principle of electromechanical energy, the coil acceleration is derived from it [11][12].

$$F = \frac{1}{2} i^2 \frac{dL}{dx} \qquad (11)$$

The inductance is based upon the location of the projectile [11][12]
The radial component force of the projectile is given by

$$F_r = \int_v f_r \, dV \qquad (12)$$

The catapult coil resistance is determined by

$$Rcoil = \frac{\rho l}{A} \qquad (13)$$

For catapult calculations
The coil inductance is determined by

$$Lc = \frac{N^2 A^2}{30A - 11Di} \qquad (14)$$

Where:
A = spiral coil area.
Di = inner diameter of the coil.
Area of the coil can be calculated by

$$Lc = \frac{N^2 A^2}{30A - 11Di} \qquad (15)$$

Where
Nc = number of turns of the coil.
W = Wire diameter of catapult coil.
S = Distance between the coil winding
The acceleration coil inductance is calculated concerning the location of the projectile.

$$La = \frac{\mu_r \mu_o N_a^2 ld(1+\frac{x}{d})}{g} \qquad (16)$$

Where,
Na= Turns of the rectangular coil.
L= rectangular coil width
X= Projectile Position.
g=length of airgap between the coils.
The acceleration coil mutual inductance is calculated with reference to the location of projectile

$$Ma = \sqrt{\frac{\mu_r \mu_o N_a^2 ld\left(1+\frac{x}{d}\right)}{g}\left((\ln(16\frac{a}{c} - 1.75)4\pi 10^{-3} a\right)} \qquad (17)$$

Where,
a= radius of a small division of the projectile.
c= projectile small division width [11][13][14].

4. CONCLUSION

The study of various technologies of multipole field electromagnetic launcher indicates that these launchers provide a high thrust, high force, high muzzle velocity, and a high acceleration force which is required to propel the projectile ahead, as compared to the conventional railgun technologies. These technologies make use of conventional capacitors to discharge the high current into the driving coil, instead of using conventional capacitors the further research will include the use of supercapacitors, because of its properties like higher specific energy, high specific power which is greater than conventional capacitors and existing batteries, and have higher energy storage capacity and the charging time required is also much lesser.

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