Design and Analysis of Cored type Multipole Field Electromagnetic Launcher (C-MFEML)

Srichandan Kondamudi, Mallikarjuna Rao Pasumarthi, Sandhya Thotakura

***Abstract*: In the group of launching drive frameworks, Multipole Field Electromagnetic Launcher (MFEML) will occupy space in replacing the chemical/hydraulic/pneumatic launching frameworks. In the existing literatures on MFEML, it was proven that it can be a best alternative for launching applications. This paper investigates the possibilities of improving the performance of existing design of coreless MFEML, by introducing Cored type Multipole Field Electromagnetic Launcher (C-MFEML). A mathematical model of C-MFEML is developed and the results are compared with that of coreless MFEML. To validate the design, a comparative statement is analyzed between Coreless and Cored MFEML.**

***Index Terms*: Multipole Field Electromagnetic Launcher, Electromagnetic propulsion, Finite Element Analysis.**

I. INTRODUCTION

An expansive scope of applications has been proposed for Electromagnetic Launchers (EML) including low/high/factor speed, little/mass, and single-shot/rep-appraised frameworks. The province of EML specialized information is inadequate to address most of concerns associated with all these applications. Century of innovative work (R. McNab, 1999) has suggested some general productivity and scaling connections for EMLs. It is normal to utilize vitality change and volumetric efficiencies (increasing speed per amp per volume) to assess an EML geometry.

Zhu et al. [1] proposed the essential outline and investigation of Multipole Field Electromagnetic Propeller. The author has shown that the Multipole field electromagnetic launcher has extraordinary pivotal segment of acceleration force and high muzzle speed. From the author observations, total acceleration time is 0.327 msec, maximum acceleration force is 266.006 kN and muzzle speed of the projectile is 232.478 m/s. According to the characteristics, the MultipoleField Electromagnetic Propeller can be considered as one of a differentiating choice.

Yingwei et al. [2] displayed a hypothetical examination and numerical assessment of a three-arrange twisty octapole field electromagnetic launcher. The researcher has suggested that it could be applied in the transportation vehicle, burrow exhausting machine and shuttle drive launcher.

Antonino et al. [3] has derived an analytical solution when the system is excited by a sinusoidal current flowing in a saddle coil moving in the axial direction through travelling wave configuration. The author has proposed a model which analyzes the induction launcher, named, Multipole field electromagnetic launcher in its travelling wave configuration.

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Wenbo et al., [4] has proposed four diverse driving coil connection patterns of sextupole field electromagnetic launcher. The author has proposed that the general impetus productivity will increment quickly as the underlying voltage of the capacitor increments.

With reference to the composition review on Multipole Electromagnetic launcher, it is seen that MFEML can be one of the interesting choice in the field of electrical drive frameworks.

A portion of the fascinating points observed in the working of Multipole field electromagnetic propelling framework are presented beneath

a) MFEML has a higher maximum projectile velocity.
b) The projectiles rely on kinetic energy at the target for their devastating effects and the MFEML device obviously needs no explosive propellants. This is a huge advantage for a ship at sea and allows the ship to carry more projectiles since no storage space needs to be allotted for the propellants
c) More accurate.
d) Compared with gauss rifle, less amperage is needed.
e) Controlled switching can be achieved.

But, basic design of Coreless MFEML is suffering with following insufficiencies (a) more flux leakages due to air core, (b) Inductance formulae mentioned is not depending on the position of the projectile, (c) Negligible thickness of current sheet was considered (Wenbo et al., 2013) and (d) Force was calculated by neglecting the leakage fluxes.

This paper proposes a plan to decrease the flux leakages by presenting core type MFEML. The schematic in Fig. 1 shows the essential sections of a Coreless Multipole Electromagnetic Launcher (MFEML), including the electromagnetic poles, projectile and barrel. The source of magnetic field is an electromagnet, which is energized with a DC current. Based on the depth of penetration of flux lines into the projectile, Lorentz drive is applied on projectile. The force applied on the projectile in the MFEML is axisymmetric like in ordinary fuel based firearms

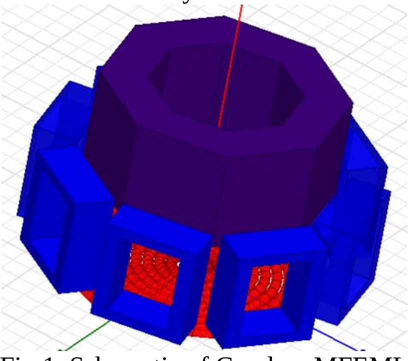

Fig.1. Schematic of Coreless MFEML

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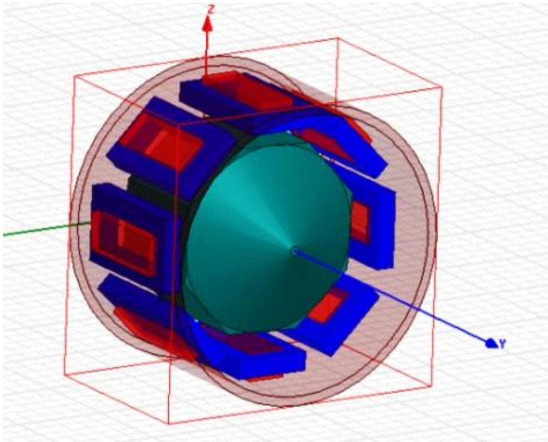

Fig. 2.Schematic of proposed Cored MFEML

In Fig. 2, schematic of the proposed Cored type MFEML is shown. Coils are housed on the fixed structure made with conducting material, which will decrease the reluctance of the framework, and will expand the depth of penetration of flux lines into the projectile.

The paper is organized as follows. Section- I reveal the till date research on MFEML and list out some of the issues that has occurred in analysis of Coreless MFEML. Section-II is devoted to illustrate the geometrical configuration and parametric analysis of Cored type MFEML. In Section-III, Coreless MFEML and Cored type MFEML are compared in magnetic aspects, and electrical, magnetic equivalent circuits are developed. In Section-IV, result analysis is displayed for various projectile weights and the observations are listed out.

II. GEOMETRICAL CONFIGURATION OF C-MFEML

The basic geometrical configuration of C-MFEML is presented in Fig. 3.

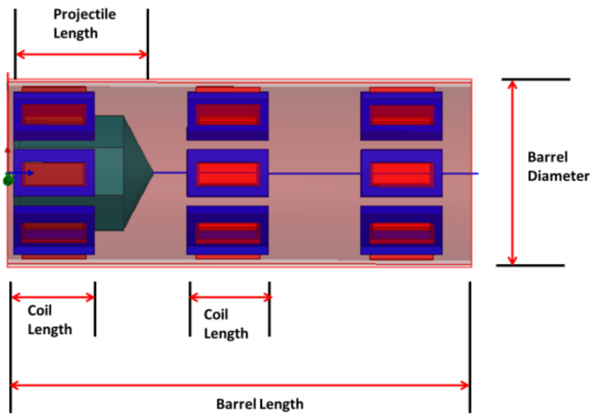

Fig.3. Geometrical configuration of Cored type MFEML

The design parameters of a single stage C-MFEML are presented in Table I.

Table 1. Design Parameters of C-MFEML

Symbol	Description
d_w	Diameter of the wire
t	Thickness of the coil
l_c	Length of the Coil
l_g	Air-gap length
d_p	Diameter of the projectile
d_b	Barrel Diameter
h_c	Height of the coil

Turns per layer
$Turnsperlayer = f(tmax, d_w)$ (1)
Winding thickness
$t = f(number\ of\ turns, d_w, fill\ factor)$ (2)
Length of the Coil
$l_c = f(number\ of\ layers, d_w)$ (3)
Length of the Wire
$l_w = f(w_c, h_c)$ (4)

The equation 1, 2, 3 & 4 exhibits the correlation between each parameter, and helps in forming parametric analysis of the launcher.

Table 2. Parametric analysis of C-MFEML

Dimensional Parameters	Area of copper wire for one turn
	Thickness of coil
	Depth of coil
	Coil inner diameter
	Coil outer diameter
	Air-gap length
	Height of the coil
	Length of copper wire
Material Parameters	Current Density
	Permeability of free space
	Permeability of material
	Volume resistivity of Copper
	Volume resistivity of Aluminum
Magnetic property based parameters	Electromagnetic thrust / Force
	Equivalent air-gap
	Coil Input Phase Current
	Current Density
	Coil inductance
	Coil Resistance
	Coil Reactance
	Muzzle Velocity
	Acceleration
Performance based parameters	Electromagnetic thrust / Force
	Current Density
	Coil Inductance
	Coil Resistance
	Input Power
	Output Power

From the parametric analysis (in shown Table 2) and observations involved in the parameter specifications, few variables are identified which will strongly influence the design of C-MFEML. They are required velocity, distance of launch, time of launch, weight of projectile, projectile length, length of the launch barrel, input voltage/current, diameter of the drive coil and length of the each drive coil.

III. MATHEMATICAL MODELING OF C-MFEML

A. Electrical equivalent circuit

The electrical equivalent circuit of the C-MFEML is shown in Fig. 4. The electrical parameters like resistance, inductance are derived from the dimensions of the single stage C-MFEML and projectile structures. According to the Kirchhoff's voltage law, the governing voltage equation can be written as

$$V(t) = R_a I + L\frac{dI}{dt} + \frac{1}{C}\int i dt \quad (5)$$

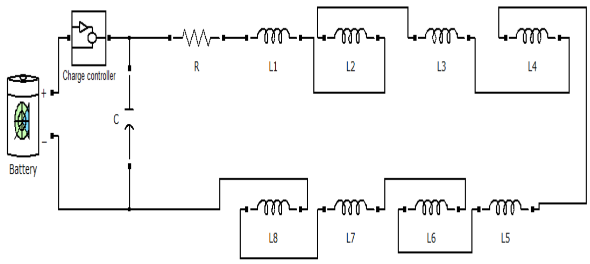

Fig. 4. Electrical Equivalent circuit of single stage C-MFEML

B. Magnetic Flux Flow

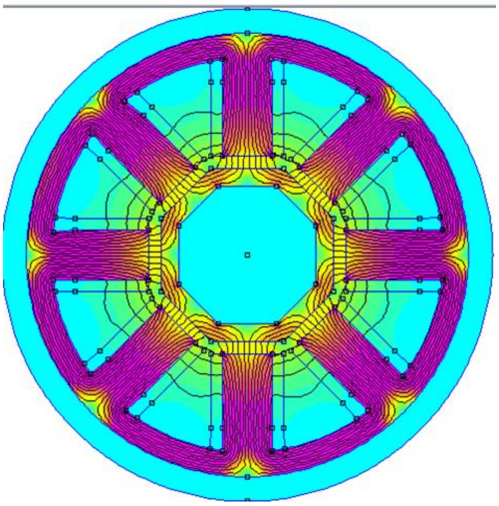

Fig. 5. Flux flow of C-MFEML

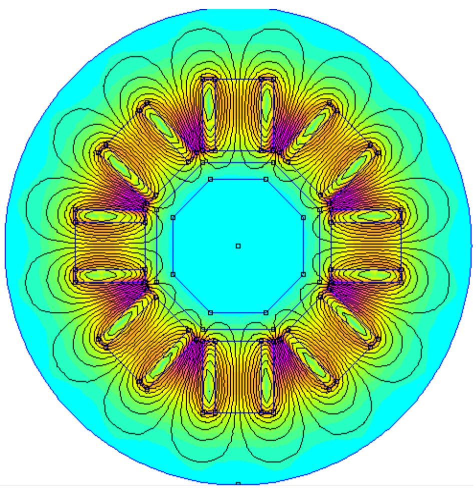

Fig. 6. Flux flow of MFEML

Fig 5.shows the flux flow in C-MFEML and Fig 6. shows the flux flow in MFEML. Flux flow diagram will exhibit the amount of flux linkages in the projectile of the system. With reference to Fig.5 & Fig.6, maximum flux density attained in C-MFEML is 1.051 Tesla, where as in MFEML is $4.532*10^{-3}$ Tesla; maximum flux intensity in C-MFEML is $1.576*10^{6}$ A/m, where as in MFEML is $3.93*10^{3}$ A/m; current density in C-MFEML is 1.904 MA/m^2, where as in MFEML is 0.245 MA/m^2. (All the given statistics for M15 steel as core).

In Table 3, comparison of proposed C-MFEML and MFEML is attained. Based on the Table 3, C-MFEML is having better flux linkages with projectile, compared to MFEML. Also in the Table 3,4,5 & 6 different core materials are tested as the core of the C-MFEML.

Table 3. Comparison of Proposed C-MFEML with MFEML – Magnetic properties

Magnetic parameters	MFEML	C-MFEML
Material used in Core	Air	M15 Steel
Max. Flux density, (Tesla)	0.0047702	1.10644
Max. Flux Intensity, (A/m^2)	4138.14141	1658712
Max. Current Density, MA/m^2	0.25833385	2.0042578

Table 4. Comparison of Proposed C-MFEML with MFEML – Magnetic properties

Magnetic parameters	MFEML	C-MFEML
Material used in Core	Air	1020 Steel
Max. Flux density, (Tesla)	0.0047702	1.08359
Max. Flux Intensity, (A/m^2)	4138.14141	1724924
Max. Current Density, MA/m^2	0.25833385	2.004257

Table 5. Comparison of Proposed C-MFEML with MFEML – Magnetic properties

Magnetic parameters	MFEML	C-MFEML
Material used in Core	Air	Supermalloy (Nickel alloy)
Max. Flux density, (Tesla)	0.0047702	1.076235
Max. Flux Intensity, (A/m^2)	4138.14141	2097318
Max. Current Density, MA/m^2	0.25833385	2.00425783

Table 6. Comparison of Proposed C-MFEML with MFEML – Magnetic properties

Magnetic parameters	MFEML	C-MFEML
Material used in Core	Air	Hiperco-50 (Cobalt Iron)
Max. Flux density, (Tesla)	0.0047702	1.097386
Max. Flux Intensity, (A/m^2)	4138.14141	1749066
Max. Current Density, MA/m^2	0.25833385	2.0042578

In Table 3, 4, 5 & 6, comparison of proposed C-MFEML and MFEML is attained. Based on the Table 3, 4, 5 & 6, C-MFEML is having better flux linkages with projectile, compared to MFEML. Also in the Table 3, 4, 5 & 6, different core materials are tested as the core of the C-MFEML.

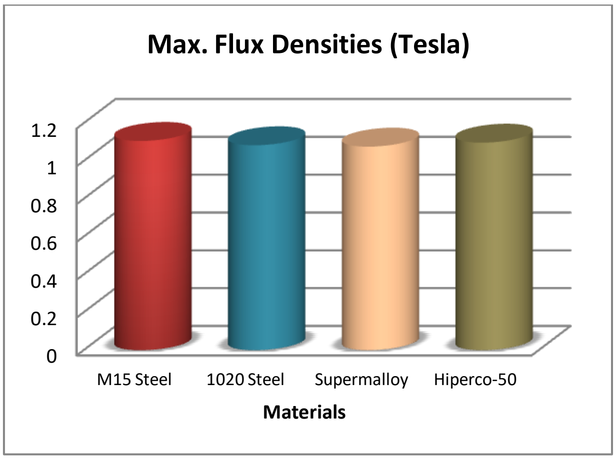

Fig. 7.B_{max} profile for various core materials

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From Fig. 7 & 8, it is observed that M15 Steel when used as core in MFEML will produce more flux density compared to Steel 1020, Supermalloy and Hiperco-50. Maximum flux intensity is more in Supermalloy. If flux intensity and flux densities are more, then the amount of flux linkages will improve. So, the amount of magnetic flux leakages in the C-MFEML is less than coreless MFEML.

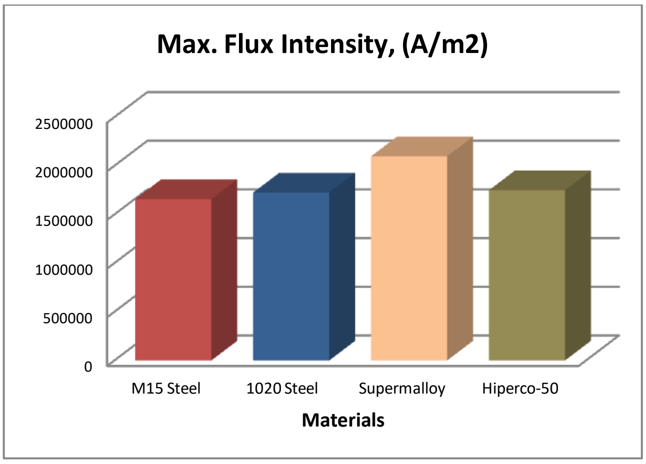

Fig. 8.B_{max} profile for various core materials

C. Magnetic Equivalent Circuit

With reference to the Flux flow diagram, various flux paths are identified. The flux path is assumed to have a flux of ϕ in the induction coil. It crosses the air gap, splits evenly in the projectile, and then re-crosses the air gap to the other side of the coil.

The magnetic circuit of a coil is represented Fig.9. By using magnetic circuit, equivalent reluctance values are calculated, which conclude with finding the value of inductance of the coil based on the position of the projectile in the coil. Coil inductance calculation is performed for two main projectile positions i.e. when the projectile is completely outside the coil, and when the projectile is fully inside the coil. Magnetic circuit of the C-MFEML when the projectile is completely inside the coil is presented in Fig. 9.

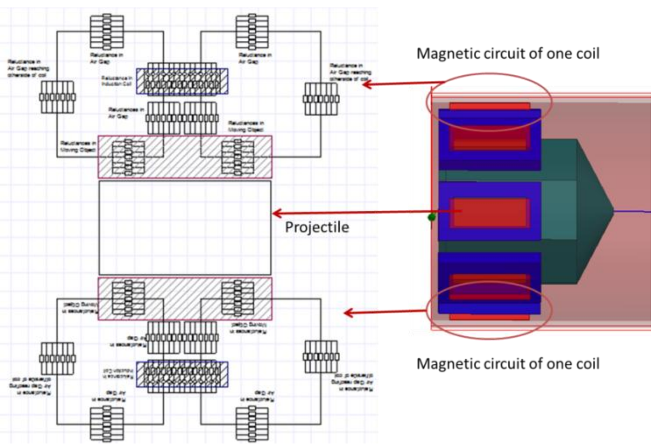

Fig. 9.Magnetic Circuit of C-MFEML (Right side View)

In similar way, magnetic circuit of the C-MFEML is obtained when projectile is completely outside the coil. Minimum inductance is attained when projectile is completely outside the coil; Maximum inductance is obtained when projectile is entirely inside the coil. The minimum inductance of the drive coil is nothing but the self-inductance of the coil. The maximum inductance value is calculated from the energy conversion method. Finally the inductance profile is expresses as [5].

$$L = L_m \left[1 + \sin\left(\frac{\pi}{l_c} x\right)\right] + L_{min} \qquad (6)$$

Where, $L_m = \frac{L_{max} - L_{min}}{2}$

IV. Comparison of C-MFEML with MFEML: Performance Aspects

The single stage model of a MFEML and C-MFEML are simulated to compare their performance. The input specifications considered for attaining correlation between the two launchers are presented in Table 7.

Table 7. Input Specifications

Symbol	Parameter	Value
lp	Projectile length	0.1 m
dp	Projectile diameter	0.03 m
M	Mass of the Projectile	1 kg
dw	Diameter of the Wire	0.45*10^-3 m
lg	Length of Air-gap	0.1*10^-3 m
µ0	Permeability of Air	4*pi*10^-7
N	Number of Turns	1300
lc	Length of the Coil	0.02 m
Nl	Number of Layers in Coil	21
V	Input Voltage	220 V
ŋ	Mechanical translational viscous coefficient	0.1 N/(m/s)
	Core material used	M15 Steel

A. Force Profiles

The force profiles of both the launchers for same input parameters are presented in Fig.10& 11.

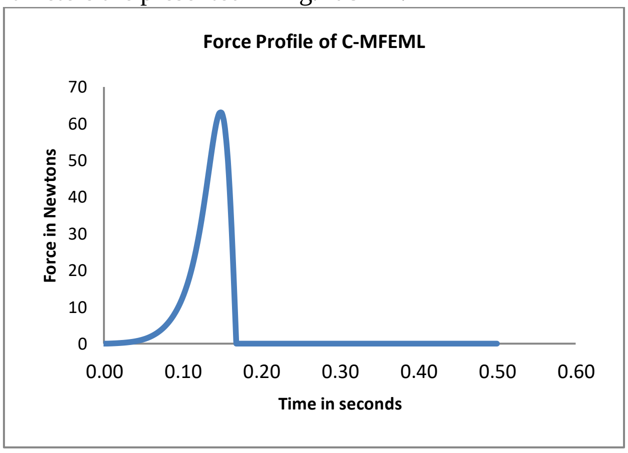

Fig. 10.Force profile of C-MFEML

From Fig. 10&11, it is realized that C-MFEML produced maximum force of 62.88 N in 0.19 sec. Whereas MFEML produced maximum force of 8.46 N in 0.35 sec. Force value is more in C-MFEML when compared with MFEML. It is because the amount of magnetic flux linkages is more in C-MFEML than MFEML.

B. Velocity Profiles

The velocity profiles of both the launchers for same input parameters are conferred in Fig.12 &13.

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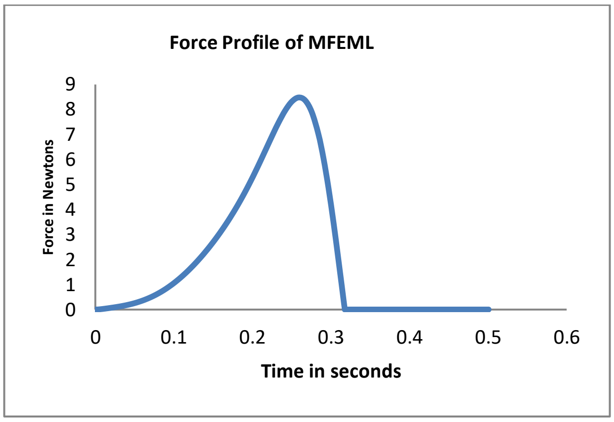

Fig. 11.Force profile of MFEML

From the Fig. 12& 13, it is recognized that, in C-MFEML, projectile velocity is 2.84 m/sec at 0.19 sec. And in MFEML, projectile velocity is 1.05 m/sec at 0.35 sec. So, by using core in C-MFEML, the amount of velocity can be increased. If a low reluctance material is selected as core, the amount of velocity can be increased.

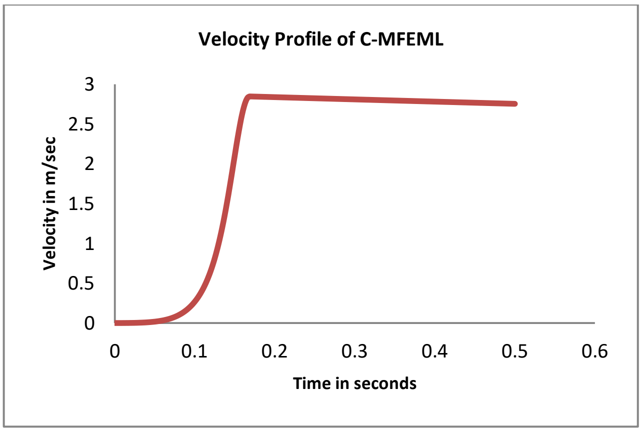

Fig. 12.Velocity profile of C-MFEML

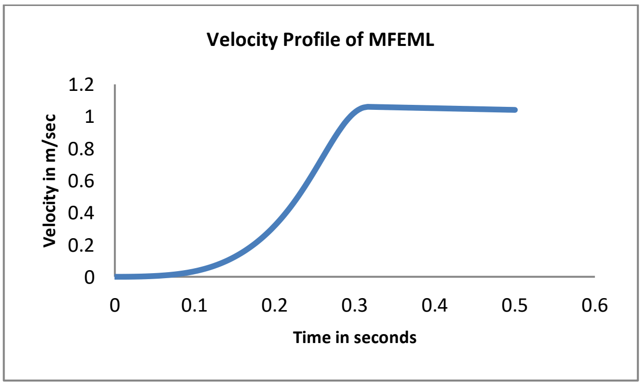

Fig. 13.Velocity profile of MFEML

V. CONCLUSION

This paper presents detailed contrast between Multipole Field Electromagnetic Launcher (MFEML) and Cored type Multipole Field Electromagnetic Launcher (C-MFEML) under various aspects. From the result analysis, C-MFEML (M15 steel core) has produced maximum force of 62.88 N, to propel the projectile (mass of 1kg) with a velocity of 2.84 m/sec, whereas coreless MFEML produced maximum force of 8.46 N, to accelerate the projectile with a velocity of 1.05 m/sec. So, the values of force and velocities are giving a statement that if a core is used, the performance of the MFEML can be enhanced. In this paper, a feasibility analysis of different core materials is observed. M15 Steel has maximum flux density of 1.10644 Tesla, whereas Steel 1020, Supermalloy(Nickel Iron alloy), Hiperco-50(Cobalt Iron) materials are having little lesser flux density. The material analysis will expand the options to use various soft iron materials as core. In summary, Cored-MFEML is promising for more accelerating force and output velocities, which will bolster the use of electrical propulsion in the nearby future.

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