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Coil Gun Electromagnetic Launcher (EML) System with Multi-stage Electromagnetic Coils

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An electromagnetic launcher (EML) system accelerates and launches a projectile by converting electric energy into kinetic energy. There are two types of EML systems under development: the rail gun and the coil gun. A railgun comprises a pair of parallel conducting rails, along which a sliding armature is accelerated by the electromagnetic effects of a current that flows down one rail, into the armature and then back along the other rail, but the high mechanical friction between the projectile and the rail can damage the projectile. A coil gun launches the projectile by the attractive magnetic force of the electromagnetic coil. A higher projectile muzzle velocity needs multiple stages of electromagnetic coils, which makes the coil gun EML system longer. As a result, the installation cost of a coil gun EML system is very high due to the large installation site needed for the EML. We present a coil gun EML system that has a new structure and arrangement for multiple electromagnetic coils to reduce the length of the system. A mathematical model of the proposed coil gun EML system is developed in order to calculate the magnetic field and forces, and to simulate the muzzle velocity of a projectile by driving and switching the electric current into multiple stages of electromagnetic coils. Using the proposed design, the length of the coil gun EML system is shortened by 31% compared with a conventional coil gun system while satisfying a target projectile muzzle velocity of over 100 m/s.

Keywords : EML, electromagnetic launcher, coil gun, multi-stage, muzzle velocity

1. Introduction

In chemical launcher systems such as firearms and satellite launchers, chemical explosive energy is converted into mechanical dynamic energy. The system must be redesigned and remanufactured if the target velocity of the projectile is changed. In addition, such systems are not eco-friendly. In contrast, electro-magnetic launcher (EML) systems convert electric energy into mechanical energy. Thus, such systems are very eco-friendly and can control the muzzle velocity of the projectile by controlling the electric current in the electromagnetic coils. EML systems are under active research and development for a variety of applications worldwide [1].

Two types of EML systems have typically been studied in past years. The first type is the rail gun EML system, wherein a projectile is placed between a pair of rails connected to a direct current (DC) power supply. The current flows through the brush of the projectile by passing the current on the rail. Two rails and conductive projectile form a strong magnetic field by creating a loop in the top and bottom of rails. This field generates a Lorentz force with flowing current in the projectile. A force $F = J \times B$ occurs, where J is the current density on the rail and B is the magnetic flux density. The projectile is propelled by the force. In this way, it has good efficiency in high-speed driving. Figure 1 shows a schematic diagram of a rail gun. Massive heat is created due to the friction of the projectile leaving the device. It is possible for the rails, barrel, and all equipment attached to melt or be irreparably damaged [2, 3].

The second type of system is the coil gun EML system, which propels the projectile by electromagnetic force caused by Fleming's right hand rule when the electric current energizes the electromagnetic solenoid coils. That is, the electromagnetic force of the coils attracts and launches the projectile. The projectile may has the contact to the flywheel tube if it is not guided at center of flywheel tube.

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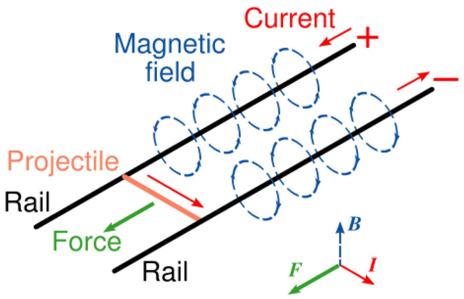

Fig. 1. (Color online) Principle of rail gun.

When the projectile is launched in the coils, the projectile has radial force (F_r) by gravity to the mass of projectile. Currently, various studies to minimize the radial force are under way. If the projectile is centered on the axis of the flywheel tube, the coil gun EML system has no friction and thus no problem with heat generation [4-7].

But, a coil gun EML system has difficulty producing a high muzzle velocity for the projectile using one coil stage because of the resistance and inductance of the coil. Thus, multiple stages of coils are required to accelerate the projectile sequentially in order to obtain a high muzzle velocity. Accordingly, the size of the coil gun system is lengthened, and the cost for the installation of a coil gun EML system (such as for a satellite) is very high due to the large installation site.

We introduce a coil gun EML system that has a new structure and arrangement of multiple electromagnetic coils to reduce the length of the gun. We developed a mathematical model and simulated the device in order to demonstrate its performance. The proposed coil gun EML system is 31% shorter compared to a conventional coil gun EML system for the case of a target muzzle velocity of over 100 m/s for the projectile.

2. Coil gun EML System

2.1. Structure of coilgun and projectile

Figure 2 shows the structure of the proposed multi-stage coil gun EML system, which accelerates a projectile in sequence. The system consists of a projectile, a flywheel tube for the projectile to pass through, multiple electromagnetic coils, capacitors for charging and discharging the electric energy, a control circuit, and a power supply.

The projectile, shown in Fig. 3, consists of a magnetic substance made of Permalloy 78 for attractive interaction with the electromagnetic coil, and a nonmagnetic part (the payload for the space launch vehicle).

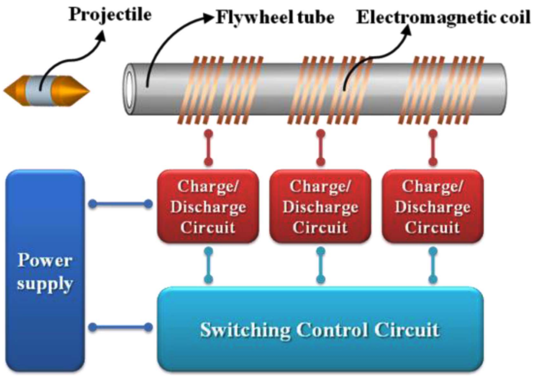

Fig. 2. (Color online) Structure of the multi-stage coil gun.

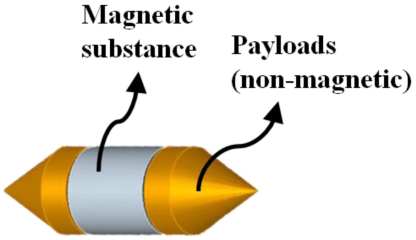

Fig. 3. (Color online) Structure of the projectile.

2.2. Magnetic system

The coils wound in the flywheel tube were simply modeled as thin shell solenoids as shown in Fig. 4. The magnetic flux density at any point P on the central axis can be expressed by the following equation for a thin shell solenoid (Fig. 4) [8, 9]:

$$B(z)=\frac{\mu_0 NI}{2}\left[z\ln\frac{\sqrt{R'^2+z^2}+R'}{\sqrt{R^2+z^2}+R}-(z-L)\ln\frac{\sqrt{R'^2+(z-L)^2}+R'}{\sqrt{R^2+(z-L)^2}+R}\right] \tag{1}$$

μ_0: Permeability constant
N: Total number of turns of wire
I: Current in the wire
L: Length of the solenoid
z: Distance from point P
R: Inside radius of the solenoid
R': Outside radius of the solenoid

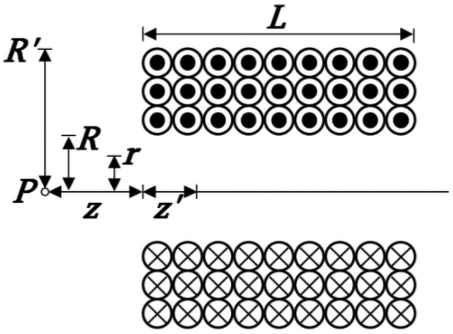

Fig. 4. Thin shell solenoid.

If radius R is small enough, the magnetic flux density at any position (r, z) is an approximation to the flux density on the central axis (0, z) shown by Eq. (1). In this case, the energy stored in the magnetic field can be expressed as

$$u(z) = \text{volume} \times \text{magnetic energy density}$$

$$= \frac{A}{2\mu_s} \int_z^{z+l} B^2(\zeta)d\zeta \tag{2}$$

A: Cross-sectional area of the magnetic body
l: Length of the magnetic body

The change in energy can be expressed as following Eq. (3) if the space is filled with the material of permeability μ_m.

$$u_m(z) = \frac{A}{2\mu_m} \int_z^{z+l} B^2(\zeta)d\zeta \tag{3}$$

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 described above:

$$\Delta u = u_m - u = \left(\frac{1}{\mu_0} - \frac{1}{\mu_m}\right)\frac{A}{2}\int_z^{z+l} B^2(\zeta)d\zeta \tag{4}$$

Thus, the muzzle velocity of a projectile is given by

$$\frac{1}{2}mv^2 = \Delta u\,,\ v = \sqrt{\frac{2\Delta u}{m}} \tag{5}$$

m: Mass of the projectile
v: Velocity of the projectile

The magnetic force F inside the magnetic field is given by Eq. (6)

$$F(z) = \frac{du}{dz} = \frac{V}{2}\left(\frac{1}{\mu_0} - \frac{1}{\mu_m}\right)(B^2(z+l) - B^2(z)) \tag{6}$$

2.3. Electric system

In order to obtain high velocity in a coil gun EML system, a large amount of electric current (~100 A) is energized into the electromagnetic coil in a very short time. A commercial electric current supply provides at most tens of amperes (~10 A). Therefore, a large capacitor is needed to charge and discharge the electric energy. The electric system can be modeled as described by Eq. (7) because the coil and capacitor are connected in series.

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int idt = 0 \tag{7}$$

Where $i(0) = 0[A]$, $V_C(0) = V_0$, and

L: Inductance of the coil
C: Capacitance of the capacitor
R: Series resistance of the coil and equivalent resistance of the capacitor

By solving Eq. (7), the electric current in the electromagnetic coil can be described as follows:

$$i(t) = Ae^{-\zeta\omega_n t}\sin(\omega_d t) \tag{8}$$

If the electromagnetic coil is still energized after the projectile passes the longitudinal center of the electromagnetic coil windings, the magnetic force of the coils pulls the projectile in the direction opposite to the launching direction, and the projectile is decelerated. This effect is called "suck back." To prevent this, the electric current on the electromagnetic coils must be cut off just before the projectile passes the longitudinal center of the coil windings.

2.4. Design of the electromagnetic coil

The final muzzle velocity of a projectile launched by a coil gun EML system increases as the mass of the projectile decreases, and the amount of supplied electric energy is greater. The supplied electric energy is proportional to the initial voltage and capacity of the capacitor. However, a maximum limitation exists on the initial voltage and capacity of the capacitor. In this study, a 0.033 F capacitor was initially charged with 400 V. To maximize the muzzle velocity of the projectile, the design of the electromagnetic coils must be optimized. First, the muzzle velocity of the projectile is greatly affected by the ratio of the longitudinal length of the electromagnetic coil windings (L_2) and the length of the magnetic body (L_1), as shown in Fig. 5. Figure 5 shows the square of the muzzle velocity according to the ratio of L_2 to L_1. When the ratio is about 0.38, the muzzle velocity is the highest [10].

A 2 mm diameter wire was used to allow a high electric current. In addition, the length of the magnetic body (L_1)

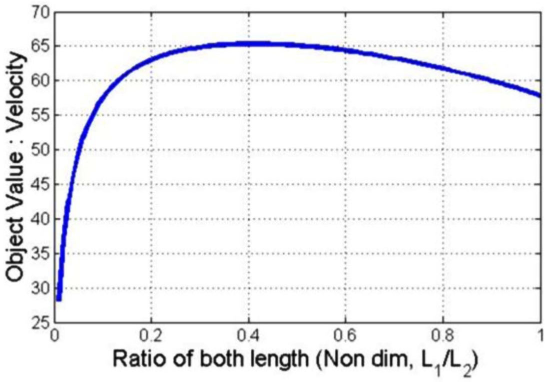

Fig. 5. (Color online) Velocity versus L_1/L_2.

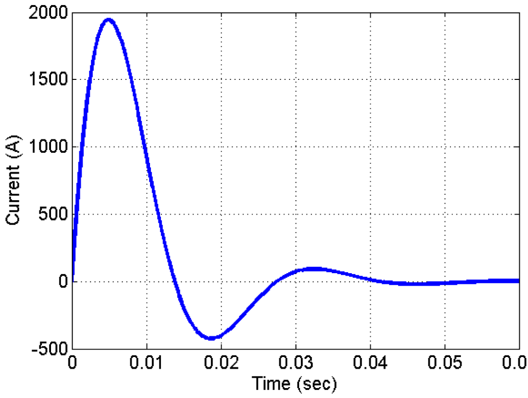

Fig. 6. (Color online) Electric current profile in a coil.

of the projectile is 7.5 mm, and the longitudinal length (L_2) of the coil windings is 36 mm. Based on our results, the number of axial coil turns is 18 and the number of radial coil turns is 8. The inductance and resistance of the coil are 0.472 mH and 0.104 Ω, respectively. Figure 6 shows the electric current of the coil at the discharge versus time.

Figure 7 and Tables 1-3 show a schematic diagram and the design specification of the multi-stage coil gun EML system, respectively.

2.5. New structure and arrangement of multi-stage electromagnetic coils

Figure 8 shows a schematic diagram of a conventional multi-stage coil gun EML system.

A conventional multi-stage coil gun EML system energizes the electromagnetic coils in sequence to accelerate and launch the projectile. The total length of a conventional coil gun EML system is determined by the product N × L, where L is the longitudinal length of each coil winding and N is the number of coil stages.

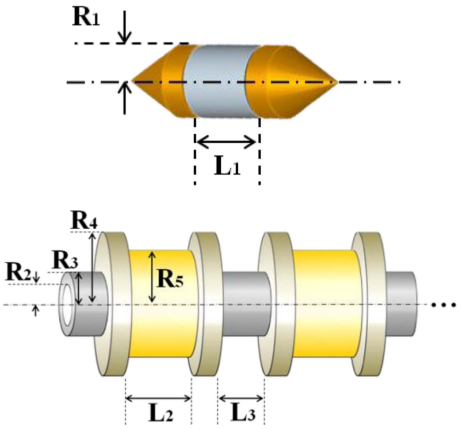

Fig. 7. (Color online) Schematic diagram of multi-stage coil gun.

Table 1. Electrical specifications.

L	Inductance of coil	4.722×10^{-4} H
R	resistance	0.104 Ω
C	Capacity of capacitor	0.033 F
V_C	Initial capacitor voltage	400 V

Table 2. Specifications of winding coil.

d	Diameter of wire	2 mm
n1	Number of axial turns of coil	18 turns
n2	Number of radial turns of coil	8 turns

Table 3. Size of projectile and coil gun.

R_1	Radius of projectile	10 mm
R_2	Inside radius of tube	11 mm
R_3	Outside radius of tube	12 mm
R_4	Outside radius of bracket	70 mm
R_5	Outside radius of winding coil	29 mm
L_1	Length of magnetic projectile	7.5 mm
L_2	Longitudinal length of coil winding	36 mm
L_3	Gap between the coils	3 mm

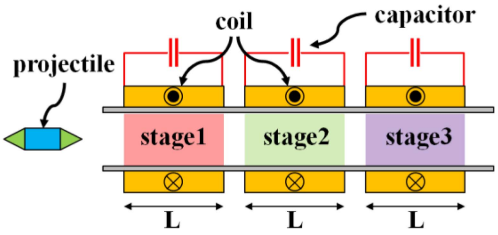

Fig. 8. (Color online) Conventional multi-stage coil gun.

To prevent 'suck- back' effect, the electric current on the electromagnetic coils must be cut off just before the projectile passes the longitudinal center of the coil windings. This system will have a non-thrust section. Accordingly, we proposed a method to eliminate non-thrust section based on the arrangements of the capacitor.

Figure 9 shows a schematic diagram of the proposed coil gun EML system. This structure was designed by focusing on the fact that the electric current in the electromagnetic coil is cut off when the projectile passes through the longitudinal center of each coil winding. The longitudinal length of each coil winding in a conventional coil gun EML system is L, and the length of each coil winding in the proposed design is L/2. The half-length coils are arranged in sequence. The first half-length (L/2) of the coil and the second half-length (L/2) of the coil are connected in series. They are energized simultaneously, and the same electric energy is obtained as in a whole length (L) of a coil in a conventional structure. When the

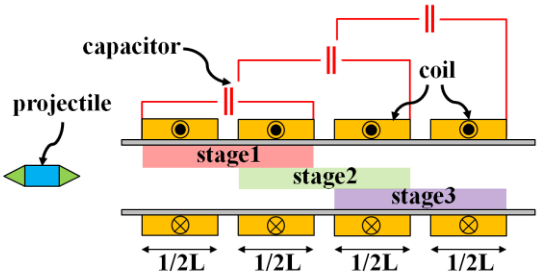

Fig. 9. (Color online) Proposed multi-stage coil gun.

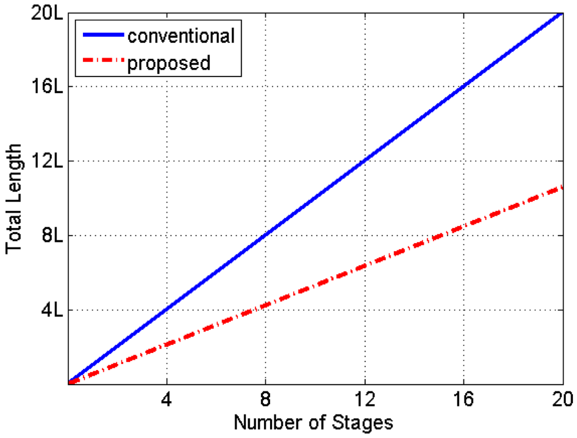

Fig. 10. (Color online) Total coil gun length versus number of stages.

projectile passes the center between the first half-coil and the second half-coil, the circuit to the first capacitor is shut off and the circuit to the second capacitor connected to the second half-coil and third half-coil is turned on. In this way, the length of the proposed coil gun EML system is 1/2(N+1)L, which is much shorter than the length of a conventional design. Figure 10 shows a comparison of the length of a conventional coil gun EML system and the proposed system. As the number of multi-stages increases, the length of the proposed system decreases compared to that of the conventional system. In the case of 20 stages, the length of the proposed system is one-half that of the conventional system.

3. Simulation

A dynamic model of the projectile of a one-stage coil gun EML system can be expressed as follows Eq. (9).

$$m\ddot{z}(t) = F(z,t) = \frac{V}{2}\left(\frac{1}{\mu_0}-\frac{1}{\mu_m}\right)(B^2(z+l,t)-B^2(z,t)) \qquad (9)$$

Muzzle velocities of a conventional coil gun EML system and the proposed system were calculated using Eq. (9). The simulations were conducted using the commercial software MATLAB® (ver.7.8.0).

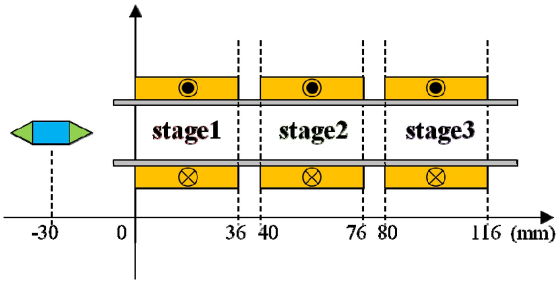

Fig. 11. (Color online) Simulation specification of conventional coil gun EML system.

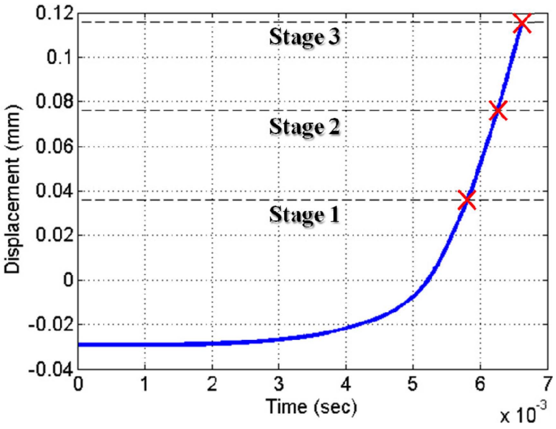

Fig. 12. (Color online) Displacement profile of the projectile of a conventional coil gun EML system.

The specification of a conventional coil gun EML system is shown in Fig. 11. Figs. 12 and 13 show displacement and velocity versus time, respectively, for the conventional coil gun EML system. "x" in Figs. 12 and 13 represents the displacement and the velocity of the projectile at the end of each stage of the electromagnetic coil.

From Fig. 13, we note that the muzzle velocity out of

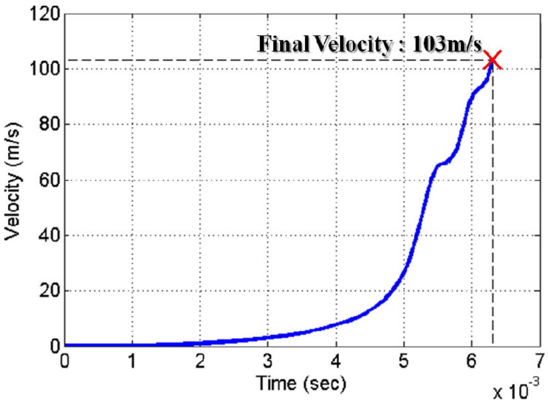

Fig. 13. (Color online) Velocity profile of the projectile of a conventional coil gun EML system.

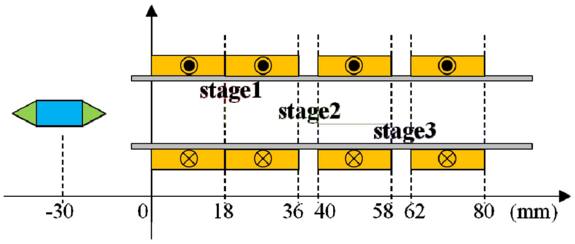

Fig. 14. (Color online) Simulation specification of proposed coil gun EML system.

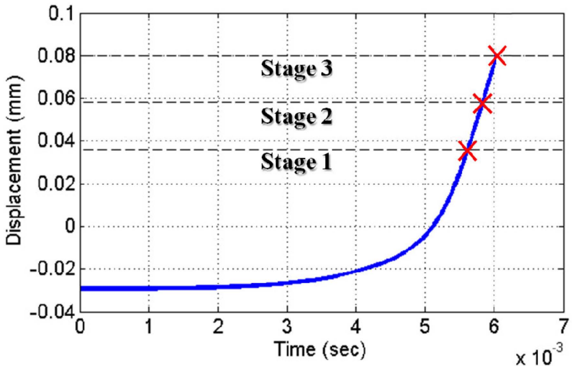

Fig. 15. (Color online) Displacement profile of projectile of proposed coil gun EML system.

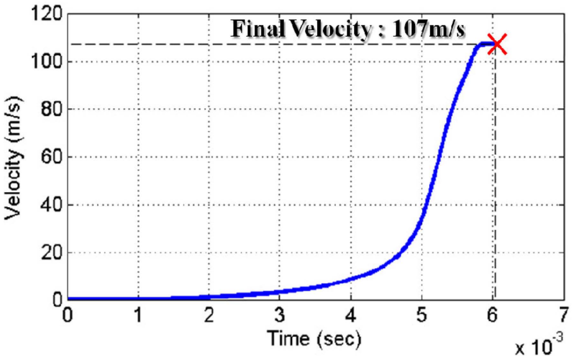

Fig. 16. (Color online) Velocity profile of projectile in proposed coil gun EML system.

stage 3 is 103 m/s.

The specification for the proposed coil gun EML system is shown in Fig. 14. Fig. 15 and 16, respectively, the displacement and velocity versus time for the proposed coil gun EML system.

Fig. 16 shows that the muzzle velocity out of stage 3 is 107 m/s. The results show that the proposed system accomplishes over 100 m/s target muzzle velocity of the projectile. Table 4 shows the comparison for the total coil gun length and muzzle velocity performance of two systems. In addition, the length size of proposed system is reduced by 31% than the conventional one.

Table 4. Comparison of conventional and proposed system.

	Conventional system	Proposed system
Total coil gun length	116 mm	80 mm
Muzzle velocity	103 m/s	107 m/s

4. Conclusion

A coil gun EML system uses multi-stage electromagnetic coils to accomplish a high muzzle velocity of the projectile. A multi-stage electromagnetic coil gun structure grows in length in proportion to the number of stages. We describe a coil gun EML system with new electromagnetic coil structure and arrangement to reduce the length of the system. Our mathematical simulation shows that the new system achieves the target muzzle velocity of the projectile with a 31% decrease in length size of system compared to a conventional system.

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