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Four Stage Induction Coilgun System Design and Analytical Calculation of Electromagnetic Expansion Force on the Stator Coil in the System

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The solenoid coil is one of the most important design component for electromagnetic induction type coil gun system. When the voltage and current are applied across the coil, a uniform magnetic field is generated inside the coil and that is proportional to the number of coil windings, and the high-density magnetic field generated by the coil can be converted to mechanical energy by applying the strong electromagnetic force to a ferromagnetic material. At this time, the interaction between the current and magnetic field of the solenoid coil generates a strong electromagnetic expansive force between each coil wire. In this paper, we introduced a four-stage induction coil gun as the launcher system using high voltage pulsed power source. Also, we proposed both the method and formula to calculate the electromagnetic expansion force acting on the multi-winding layer solenoid coil gun by using energy transfer equations. When the current flows a solenoid coil, the expansion force is generated in the radial direction of the coil. The mathematical calculation results were verified by simulated ones.

Keywords : coil gun, solenoid coil, electromagnetic force, magnetic expansive force, magnetic field

1. Introduction

Electromagnetic coilguns have been developed for several years as the guided missile launcher system to replace the conventional chemical explosion method. In general, missile acceleration through chemical energy explosion has many disadvantages in terms of flaming flash, noise, damage, and reusability. In order to solve these problems, a cold launching technology such as an electromagnetic coil gun has been applied as the next generation method for accelerating missile projectiles [1-4].

The EIC(electromagnetic induction type coilgun) is based on multi-layer solenoid coils and is operated from a high voltage power source. Fig. 1 shows the structure and operating principle of the EIC system. The EIC usually consists of two solenoid coil structures both a stator coil and an armature coil [4-6]. When high-voltage pulsed power is applied to the stator coil instantaneously, the large time-varying magnetic field passes through the armature coil. At this time, a large back EMF (Electromotive Force) is generated in the armature coil according to Faraday's law. The back EMF and reverse current generated in the armature coil create a secondary magnetic field inside the coilgun. The direction of the magnetic field generated in the armature coil is opposite to that of the main magnetic field generated in the stator source coil. In conclusion, the magnetic repulsive force is formed between the stator coil and the armature coil according to the interaction of the magnetic field generated inside the coil, and the armature coil which has gained driving force by the magnetic field could be moved to the axial direction [7-9].

However, in the cylindrical solenoid coil, the Lorentz

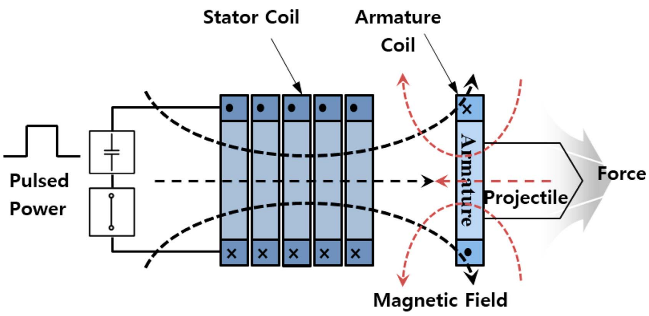

Fig. 1. (Color online) The basic concept of electromagnetic induction coil gun.

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force is simultaneously generated in each winding of the stator coil by both the current flowing through the copper wire and the magnetic field formed inside the coil. The assembly of the coilgun is composed of a multi-layer wound solenoid coil, and when the current flows through each copper wire, the physical expansion force acts on each coil winding in the radial direction. The electromagnetic expansion force acting on the coil is a major factor influencing the stability design of the coil assembly structure. Therefore, it is very important to analyze the electromagnetic expansion force acting on the solenoid stator coil when manufacturing coilgun system.

In this paper, we introduced the electromagnetic four-stage induction coil gun as the launcher system based on high voltage pulsed power source. Also, we proposed both the method and formula to calculate the electromagnetic expansion force acting on the multi-winding layer solenoid coil gun by using energy transfer equations. When the current flows a solenoid coil, the expansion force is generated in the radial direction of the coil. The mathematical calculation results were verified by simulated ones.

2. Design and Analysis Model

To develop the more powerful electromagnetic launcher, the stator coil of the EIC system is necessary to be manufactured in multiple stages to accelerate the projectile. In this paper, we designed and developed an electromagnetic four-stage induction coilgun launcher to eject heavy projectiles.

Fig. 2 shows the design and development scheme of the four-stage induction coilgun based on pulsed power voltage source. The number of turns and layers for winding coils in EIC system are determined by optimal design procedure called Taguchi method. This technique is one of the best statistical optimization method used to attain reliable design parameters within permissible limit condition. We assumed that the efficiency is the objective function as the value of ratio between the electrical input energy and the kinetic output energy of the EIC system. The design results of the coil assembly with four stators and an armature coil are shown in Fig. 2 and Fig. 3. Also, Table 1 shows design specifications of the electromagnetic four-stage induction coilgun. In terms of the coil assembly, the E-glass composite is applied to the material of the coil body such as the bobbin which is used to hold the shape of coil windings and the oxide-free copper wire is applied to each solenoid coil.

Fig. 3 shows the axisymmetric analysis model for 4-stage stator coils and an armature coil. The design model of coilgun consists of four stator coils, and the armature coil is sequentially accelerated from the position of 1st stage stator coil until it passes through the 4th stage coil.

Each coil is made of a multi-layer wound solenoid coil and its shape and dimensions are determined by the number of turns. Accordingly, the resistance, inductance, and mutual inductance components of the coil are

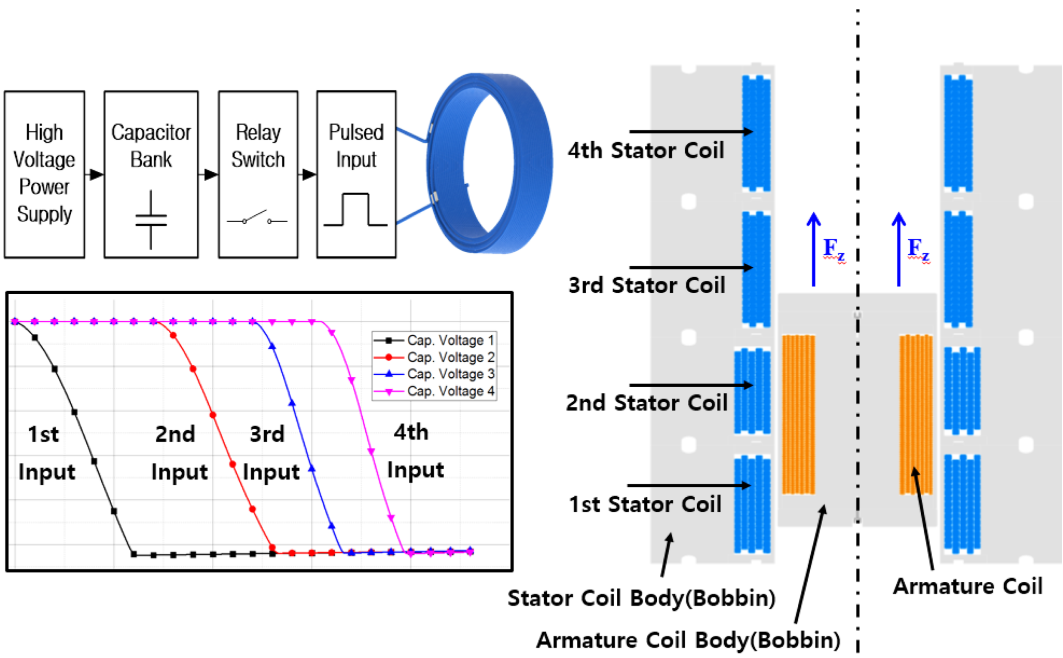

Fig. 2. (Color online) Scheme of design and development for the 4-stage induction coilgun system.

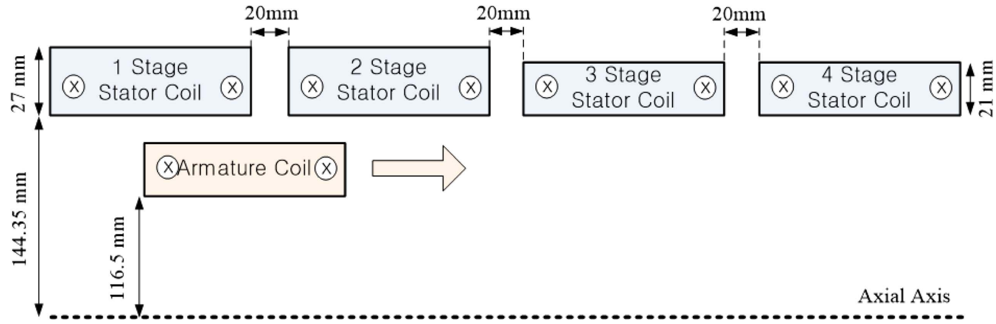

Fig. 3. (Color online) The axisymmetric design structure of 4-stage stator coils and an armature coil.

Table 1. Design specification of the stator coil assembly.

	Parameter	Value
1st stator	Number of layers	5
	Number of turns per layer	17
	Resistance [Ω]	0.0593
	Inductance [mH]	2.699
2nd stator	Number of layers	5
	Number of turns	15
	Resistance [Ω]	0.0495
	Inductance [mH]	2.218
3rd stator	Number of layers	4
	Number of turns	20
	Resistance [Ω]	0.0549
	Inductance [mH]	2.085
4th stator	Number of layers	4
	Number of turns	20
	Resistance [Ω]	0.0549
	Inductance [mH]	2.085
Armature	Number of layers	7
(Projectile)	Number of turns	65
	Resistance [Ω]	1.217
	Inductance [mH]	42.54

calculated so that the magnitude of the current generated inside the coil and the strength of the magnetic field can be mathematically calculated.

The resistance and inductance of multi-layer solenoid coil can be defined by the shape dimensions of the coil as shown in equation (1) and equation (2) below.

$$R_c = \frac{\rho l}{s} = \frac{\rho}{\pi {r_{wire}}^2} \sum_{i=1}^{N_1 L_1} \sum_{j=1}^{N_2 L_2} 2\pi r_{ij} \tag{1}$$

$$L_c = \frac{0.8(r^2 N^2)}{6r + 9l + 10d} \tag{2}$$

where R_c, ρ, r_{wire}, N_1, N_2, L_1, L_2, r, L_c, l, d are the resistance of the multi-layer solenoid coil, resistivity, the radius of wire, the number of coil turns per unit length on the horizontal axis, the number of coil turns per unit length on the longitudinal axis, the length of horizontal distance, the length of longitudinal distance, the radius of the solenoid coil, the inductance of the multi-layer solenoid coil, the thickness of the coil [6].

When the pulsed voltage is applied across the coil, the current flowing through the stator and armature coil is calculated by the voltage equation as in (3). In the coil gun structure, a reverse current is generated in the armature coil by the magnetic field generated in the stator coil and is interacted with the magnetic field generated by the source current. This is related to the mutual inductance [7, 8].

$$\mathrm{R}\begin{bmatrix} i_s(t) \\ i_a(t) \end{bmatrix} + v_z G \begin{bmatrix} i_s(t) \\ i_a(t) \end{bmatrix} + L \begin{bmatrix} di_s(t)/dt \\ di_a(t)/dt \end{bmatrix} + \mathrm{M} \begin{bmatrix} di_s(t)/dt \\ di_a(t)/dt \end{bmatrix} = \begin{bmatrix} V_s(t) \\ 0 \end{bmatrix} \tag{3}$$

where R, v_z, G, L, M, $V_s(t)$ are the resistance matrix of the circuit, the velocity of the armature coil, the mutual inductance gradient along the axial direction, the matrix of inductance, the mutual inductance matrix between the stator and armature coil, the input voltage applied to the stator coil respectively.

The total driving force on the armature coil is obtained by (4) and the reliability of following mathematical model is verified by simulated results using finite element method [7-9]. Also, the force could be expressed as mechanical equation as given in (5).

$$F_z = \sum_{k=1}^{n} \frac{M_{ak}}{dz} i_{sk} i_a \tag{4}$$

$$F_z = m a_z = m \frac{dv}{dt} = \mathrm{m} \frac{dz^2}{dt^2} \tag{5}$$

where F_z, (dM_{ak}/dz, i_{sk}, i_a, n, m, v, z are the driving force on the armature coil along the axial direction, mutual inductance gradient between the stator and armature coil, the stator current, the armature current, the number of stator coil in the coil gun structure, the mass of an armature coil, the velocity of an armature coil, the axial distance of the coil.

3. Calculation of Electromagnetic Expansion Force

The electromagnetic coil gun consists of each multi-layer solenoid coil. The multi-layer solenoid coil is wound with conductive wires and is closely related to the magnitude and direction of both the current and magnetic field generated in each individual wire. So, it is hard to calculate the electromagnetic expansion force acting on each coil one by one because the mathematical integral formula is complicated. In this paper, a simple calculation formula for the magnetic expansion force acting on the stator solenoid coil is proposed using the electromagnetic-mechanical energy conversion equation. The Fig. 4 shows the direction of the magnetic field inside the coil, the direction of the Lorentz force, and the flow chart of energy conversion when the current is applied to the solenoid coil. Assuming that the pulsed voltage is applied to the coil instantaneously and electrical and thermal losses are neglected, it can be expressed as equation (5).

$$W_{elec} = W_s + W_m \tag{6}$$

where W_{elec}, W_s, W_m are electrical energy from the voltage source, the magnetic stored energy in solenoid coil, mechanical energy acting on the coil body.

Expressing both sides of the equation as a differential equation with respect to time, the equation is as following:

$$\frac{W_{elec}}{dt} = \frac{dW_s}{dt} + \frac{dW_m}{dt} \tag{7}$$

$$\frac{W_{elec}}{dt} = v \cdot i = \frac{dW_s}{dt} + f_r\frac{dr}{dt} \tag{8}$$

where v, i, f_r, and r are the input voltage, the current in the coil, the magnetic force on the coil, the magnitude of magnetic expansion force acting in the radial direction of the coil, and the radial length of the coil.

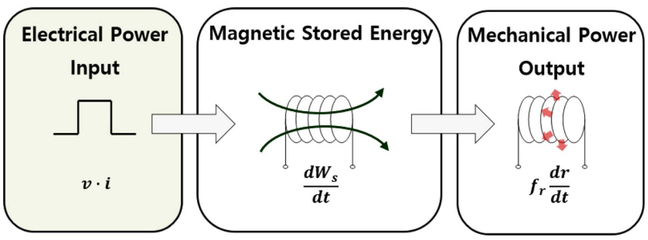

Fig. 4. (Color online) Electrical and mechanical energy conversion flow in the solenoid coil.

When the current is applied to the solenoid coil, a magnetic field which is proportional to the current is generated, and the magnetic energy which is proportional to the square of the magnetic field is stored in the coil. Therefore, the magnetic energy can be expressed as a function of current, magnetic field and coil radius.

$$W_s = W_s(i, r) = W_s(\lambda, r) \tag{9}$$

where λ means the magnetic flux linkage in the solenoid coil.

At this time, the energy stored in the solenoid coil can be defined as the product of the inductance of the coil and the current, and can be expressed as follows using the relation between the current and the inductance.

$$W_s(i, r) = W_s(\lambda, r) = \frac{1}{2}Li^2 = \frac{1}{2}\frac{\lambda^2}{L} \tag{10}$$

here, L represents the inductance of the solenoid coil. This value is expressed as the ratio of the magnetic flux linkage per unit current. In addition, if the inductance is expressed as the strength of the magnetic field for a single-layer solenoid coil of finite length, it can be expressed as the shape function of (10).

$$L(r) = \frac{\lambda}{i} = \frac{N\Phi}{i} = \frac{\mu_0 N^2 \pi r^2}{l} \tag{11}$$

where μ_0, N, Φ, l are the permeability in air, the number of turns for wires, magnetic flux, the axial length of solenoid coil respectively.

Also, the magnetic energy stored in the solenoid coil $W_s(\lambda, r)$ is formulated using the chain rule as following:

$$\frac{dW_s(\lambda, r)}{dt} = \frac{\partial W_s}{\partial \lambda}\cdot\frac{d\lambda}{dt} + \frac{\partial W_s}{\partial r}\cdot\frac{dr}{dt} \tag{12}$$

it can be expressed as equation (12) by transposing both sides of equation (7).

$$\frac{dW_s}{dt} = v \cdot i - f_r \cdot \frac{dr}{dt} \tag{13}$$

Considering the relationship between equation (11) and (12), the mechanical expansion force acting on the solenoid coil can be defined as in equation (13).

$$f_r = -\frac{\partial W_s}{\partial r} \tag{14}$$

$$f_r = -\frac{\partial W_s}{\partial r} = -\frac{\partial}{\partial r}\left(\frac{1}{2}\frac{\lambda^2}{L}\right) = \frac{1}{2}\frac{\lambda^2}{L^2}\frac{\partial L}{\partial r} = \frac{1}{2}i^2\frac{\partial L}{\partial r} \tag{15}$$

If the formula for inductance is applied to equation (14), the electromagnetic expansion force acting on the single-layer wound solenoid coil is simply calculated as follows:

$$f_r = \frac{\mu_0 N^2 i^2}{l} \pi r \tag{16}$$

The stator coil inside the coil gun system proposed in this paper is composed of a multi-layer wound solenoid coil. In this case, the inductance can be expressed as the shape function of the coil dimension, and the radius of circular coil is determined according to the number of coil turns. Therefore, the electromagnetic expansion force acting on the multi-layer solenoid coil can be finally calculated using the average radius of the coil as following:

$$f_r = \frac{\mu_0 N^2 i^2 \pi}{l} \left(\frac{r_{inner} + r_{outer}}{2}\right) \tag{17}$$

where r_{inner} and r_{outer} are the inner and outer radius of the multi-layer solenoid coil.

4. Numerical Analysis using Finite Element Method

In order to verify the calculation result of the proposed formula for the electromagnetic expansion force acting on the stator coil inside the coil gun, we performed the numerical analysis and simulated results through the finite element method were compared and reviewed with calculated ones. The design and analysis specifications of the electromagnetic coil gun presented in this paper are shown in Fig. 3 and Table 1. The drawing of an electromagnetic coil gun is modeled in two-dimensional axisymmetric condition using MagNET which is a commercial tool for electromagnetic field analysis. Fig. 5 shows the result of modeling and mesh element division. At the area of stator coil and armature coil, material properties for the conductivity and mass density of copper wire were applied. Considering the operating conditions of pulsed power source required for the coil gun, the stator coil was set to apply a 4 kV input voltage for 0 to 20 ms. In each stage of the stator coil, the voltage is sequentially switched with a time interval within 10ms step by step.

Fig. 6 shows the distribution of electromagnetic expansion force acting on each stator coil inside the coil gun. The analysis result assumes that the fixed structure supporting the stator coil is in surface contact with the coil and the radial expansion force can be computed from the magnitude of the Lorentz force per unit area acting on the stator structure.

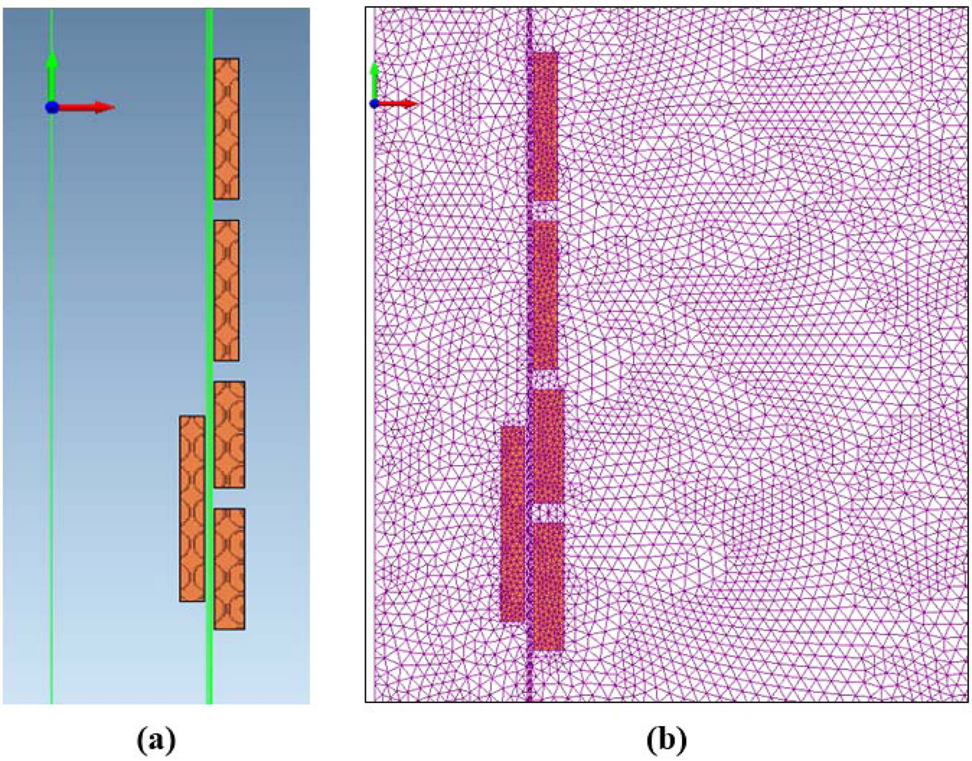

Fig. 5. (Color online) Results of axisymmetric modeling for electromagnetic induction coil gun. (a) model drawing. (b) mesh.

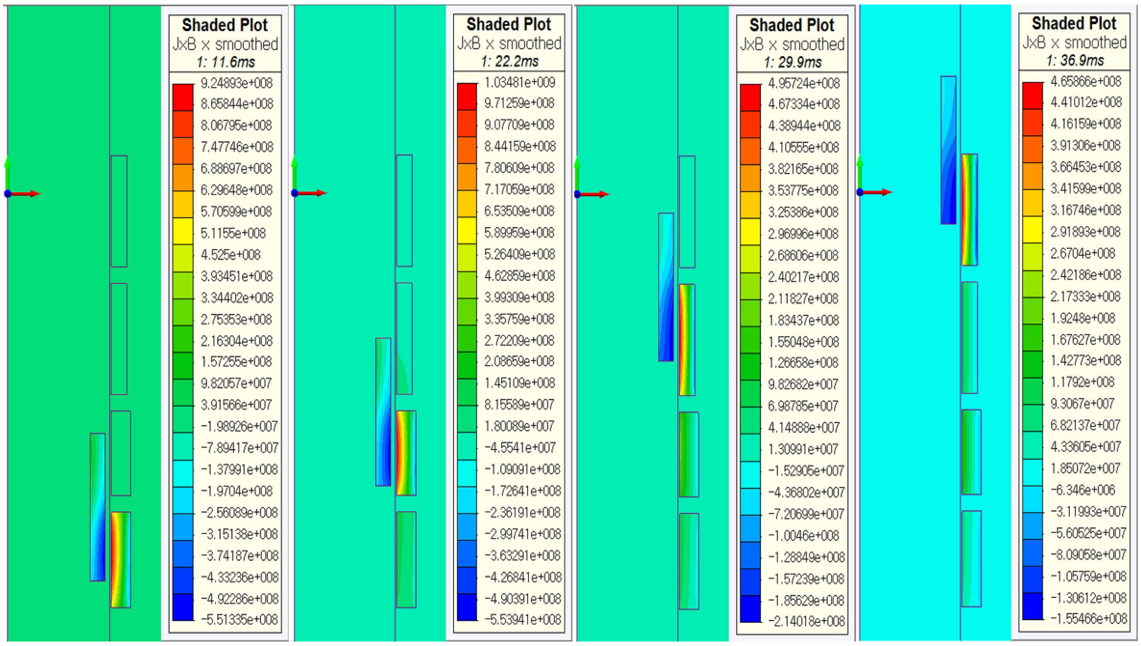

Fig. 6. (Color online) Distributions of magnetic force density on the stator coils.

5. Analysis Results and Discussions

When a large amount of current is applied to the stator coil inside the coil gun, the magnetic force proportional to the magnitude of the input current and the shape parameter of the coil is suddenly generated in each wire of coils. It could be confirmed by the proposed formula. In particular, the electromagnetic expansion force acting in the radial direction of the coil is a major factor hindering the structural stability of the coil body. Therefore, it is essential to analyze the magnetic expansion force acting on the coil in the first stage of structural design for the coil cover and support structure.

Fig. 7 shows the result that the current distribution of the each stator coil and dynamic characteristics of the armature coil inside the coil gun are simulated by finite element analysis. Fig. 8 also shows the result that the current distribution of the each stator coil and dynamic characteristics of the armature coil inside the coil gun are calculated by the proposed formula in this paper. These represent simulated results of launching characteristics for the electromagnetic coilgun system with respect to 4 kV

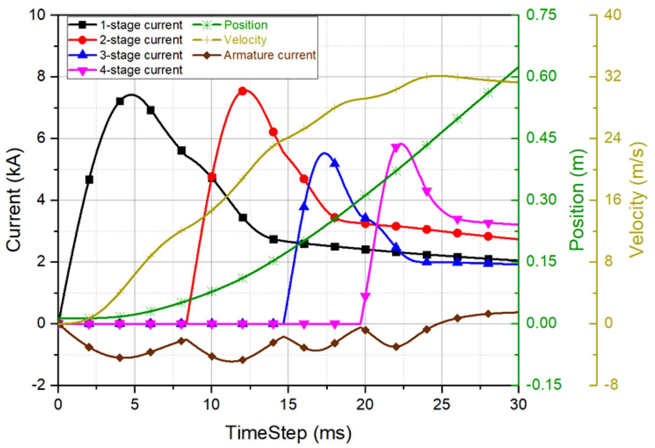

Fig. 7. (Color online) The current distribution on the each coil and dynamic characteristics of armature coil inside the coilgun by FEM simulated result.

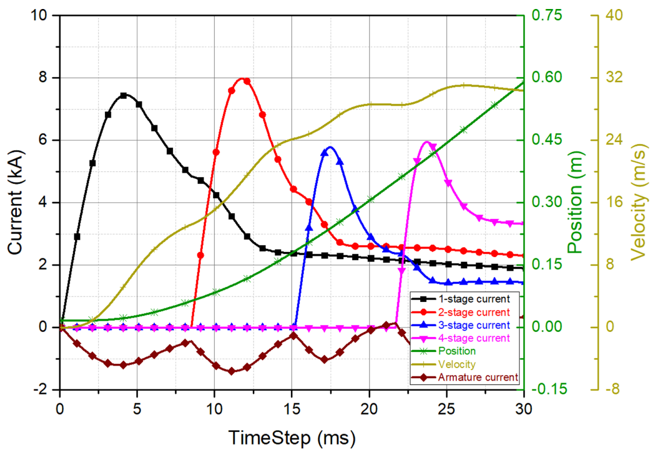

Fig. 8. (Color online) The current distribution on the each coil and dynamic characteristics of armature coil inside the coilgun by mathematical calculated result.

Table 2. The maximum current on the each stator coil.

Item	Maximum Current [kA]		Error Rate [%]
	FEM Simulated	Mathematical Calculated	
1st Stator	7.32	7.52	2.73
2nd Stator	7.81	7.95	1.79
3rd Stator	5.63	5.75	2.13
4th Stator	5.85	5.94	1.54

pulsed input voltage respectively. In the multi-stage induction coil gun system, the current is applied to each stator coil step by step according to the moving distance of the armature coil. In addition, when a constant voltage is applied to the stator coil, the mutual inductance and magnetic field distribution inside the stator coil vary according to the moving distance and speed of the armature coil. In conclusion, the reason why the magnitude of the current is different in the same coil is that the magnitude of the electromotive force induced in the stator coil is different in the section where the armature coil accelerates to its maximum speed.

Table 2 shows the magnitude of the maximum current flowing through the stator coil. The switching time and interval of the pulsed input voltage to the four stator coils are within 10 ms. From the simulated result, it could be confirmed that the direction of the current flowing through the armature coil is opposite to that of the current flowing through the stator coil. We verified that calculated results using the mathematical equation proposed in this paper has an error range of less than 5% compared to simulated results using the finite element method.

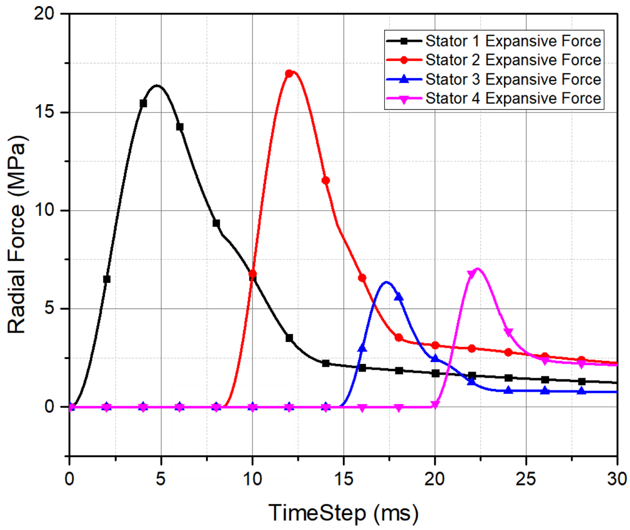

Fig. 9. (Color online) Magnetic expansion force on the each stator coil by FEM simulated result.

The driving force acting on the armature coil and the moving position of the armature coil were calculated according to the influence of the mutual magnetic field generated by the armature coil and the stator coil current. The maximum velocity through the four-stage stator coil reached about 30 m/s.

Fig. 9 shows the electromagnetic expansion force on each stator coil by FEM simulated results. Also, Fig. 10 shows the expansion force on each stator coil by calculated ones. These are the results of calculating the magnitude of the expansion force per unit area of the stator coil body by applying the mathematically calculated formula to the design model. The shape dimensions of the coil, circuit constants, and input current were applied in the same way as the finite element analysis conditions. Previously, the maximum current of 7.95 kA was generated in the stator coil inside the coil gun proposed in this paper. According to the proposed formula for the electromagnetic expansion force, it was confirmed that the expansion force is proportional to the square of the number of turns of the multi-layer wound solenoid coil

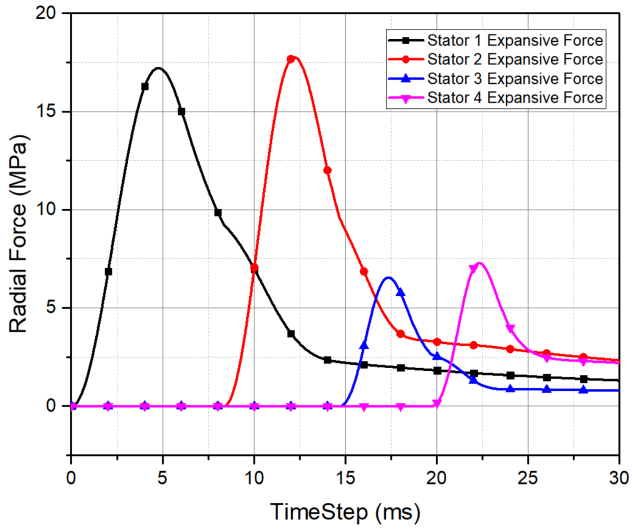

Fig. 10. (Color online) Magnetic expansion force on the each stator coil by mathematical calculated result.

Table 3. The maximum magnetic expansion force on the each stator coil body.

Item	Expansion Force [MPa]		Error Rate [%]
	FEM Simulated	Mathematical Calculated	
1st Stator	16.52	17.21	4.01
2nd Stator	17.04	17.76	4.22
3rd Stator	6.26	6.54	4.47
4th Stator	6.98	7.28	4.29

and the square of current occurred in the coil. Table 3 shows the magnitude of the maximum expansion force generated in each stator coil module.

Comparing the analysis result using the mathematical model formula and the simulation result using the finite element method, it can be confirmed that the error range is within 5% as given in Table 3.

6. Conclusion

In this paper, we introduced the structure and operating principle of the electromagnetic 4-stage induction coilgun system. In addition, the mathematical modeling method and electromagnetic simulation results for the analysis of the dynamic characteristics of the coil gun were described. The coil gun was composed of a multi-layer wound solenoid stator coil and an armature coil, and a large amount of current had to flow through the stator coil for launching the armature coil. When a large current flows through the stator coils, it could be confirmed that electromagnetic expansion force proportional to the square of the coil current is generated in each stator coil.

This paper focused on specifying the mathematical calculation method for the electromagnetic expansion force generated in the multilayer solenoid stator coil inside the coilgun. By using the proposed electromagnetic-mechanical energy conversion equation, it was possible to present the expansion force calculation formula that enables more efficient and intuitive analysis. In conclusion, the expansion force acting in the radial direction of the solenoid stator coil could be expressed as a function of the shape and structural factor of the wound coil and the magnitude of the current. The validity of the mathematical equation for the magnetic expansion force proposed in this paper was verified through the simulated results for electromagnetic filed analysis using the finite element method.

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