An Optimal Design of Capacitor-Driven Coilgun

Seog-Whan Kim, Hyun-Kyo Jung, and Song-Yop Hahn

***Abstract*—This paper presents an analysis and optimal design of a capacitor-driven inductive coilgun. An equivalent circuit is used for a launch simulation of the coilgun. The circuit equations are solved together with the equation of motion of the projectile by using the Runge–Kutta method. The numerical results are compared with the experimental values to verify the usefulness of the developed simulation program. It is shown that the numerical and the experimental results are in a good agreement. In the design of the system the optimization is achieved by employing the genetic algorithm. The resultant specifications of the coilgun optimally designed by the proposed algorithm are tested by experiment. Finally the obtained results are compared with those designed by approximate equations and by linear search methods as well. It is found that the proposed algorithm gives a better result in the energy efficiency of the system, namely it enables one to obtain a higher muzzle velocity of the projectile with the same amount of energy.**

I. Introduction

ELECTROMAGNETIC launch systems have advantages compared with the existing chemical launch systems. Generally the electromagnetic launchers are categorized into two kinds of systems: railguns and coilguns. The railgun is suitable for small projectiles and conceptually simple. However, it has inherent problems and limitations. On the other hand, the coilgun is not suitable for small projectiles, but only for large launch masses. Especially, the capacitor-driven inductive coilgun which is almost free from the friction between barrel and sleeve is recommended for rapid acceleration. It can be easily installed and repeatedly used, the electromagnetic launch does not damage the launch devices, and the force exerted on the projectile is distributed uniformly [1]–[3].

The inductive coilgun is relatively complex. Designing the coilgun based on an analytic approach is not an easy task, because the whole launch process is in a transient state and the mutual inductances between the driving coils and the projectile sleeve change with time. Hence it is necessary to rely on numerical approaches to design a coilgun with good launch characteristics. The design using the numerical approaches usually requires the system modeling technique as well as optimization algorithm [4]–[8].

In this paper, an optimal design of the capacitor-driven inductive coilgun is presented by using a numerical approach. For the design a launch simulation is combined with an optimization algorithm. An equivalent circuit is used for the simulation, and its circuit equations are solved numerically together with the equation of motion of the projectile. To illustrate the usefulness of the simulation an experimental verification has been performed concerning the optimization problem of the coilgun, the genetic algorithm to search for a global maximum is applied to the optimization of the design parameters. Finally the sample design of a one-section coilgun demonstrates the potential of the proposed design method. The use of capacitor-driven polyphase excitation of the coilgun, and the approach used for the work reported here, are based on the earlier work by Zabar's group at Polytechnic [4], [5], [8], [9].

Manuscript received April 10, 1993; revised September 21, 1993.

S. W. Kim and S. Y. Hahn are with Department of EE, Seoul National University, Seoul 151-742, Korea.

H. K. Jung is with Department of EE, Kangwon National University, Chuncheon 200-701, Korea.

IEEE Log Number 9214576.

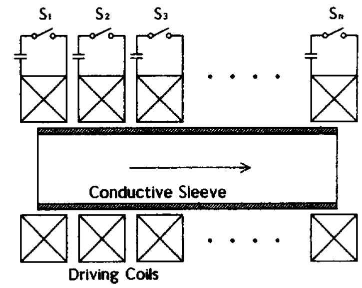


Fig. 1. Structure of a capacitor-driven coilgun.

II. Structure and Mechanism of Coilgun

Fig. 1 shows the structure of a capacitor-driven inductive coilgun [4]. The coilgun consists of a moving sleeve and driving coils fixed on the barrel. The capacitor bank is connected to the coils as an energy source. Due to the sequential switching from switch S_1 to S_n, a traveling field is established inside the barrel and eddy currents are induced on the surface of the conductive sleeve. The projectile is accelerated by the electromagnetic force from the interaction between the traveling magnetic field and the eddy currents in the sleeve.

In practical cases, a simpler structure is required than the structure shown in Fig. 1 which requires many switching devices and some complex control circuits. As shown in Fig. 2, the six-coil structure can be a simple and suitable one. The driving coils are connected for generating four poles.

0018-9464/94$04.00 © 1994 IEEE

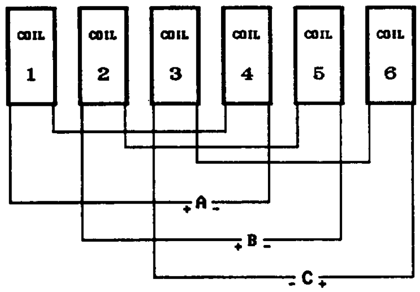


Fig. 2. Coil connection of a four-pole type coilgun.

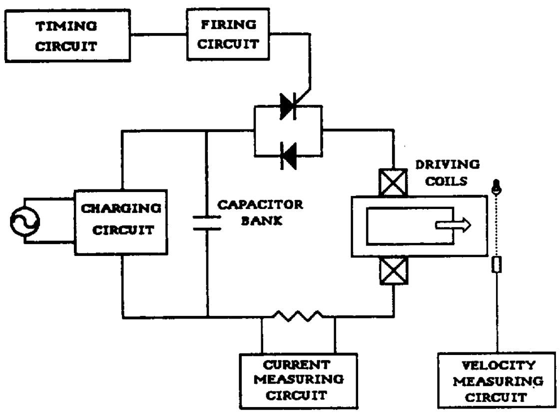


Fig. 3. Experimental system.

III. Launch Simulation and Experiment

Since the distribution of eddy currents in the sleeve is not uniform, the sleeve is assumed to be composed of shorted coils. The inductances of the equivalent circuit are calculated by using the flux integration method [10]. The circuit equations and the equation of motion of the projectile are represented as follows [4]:

$$\{[L] + [M]\} \frac{d}{dt}[I] = [V] - [R][I] - v_p[G][I], \quad (1)$$

$$[C] \frac{d}{dt}[V_c] = -[I_d], \quad (2)$$

$$M_p \frac{dv_p}{dt} = \frac{1}{2}[I]^T[G][I], \quad (3)$$

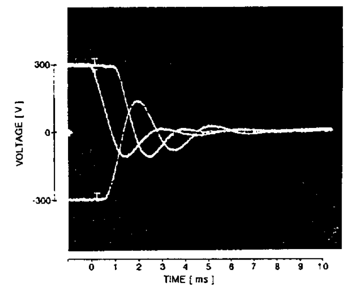
$$\frac{dx}{dt} = v_p, \quad (4)$$

where $[G] = d/dx\,[M]$, and M_p and v_p are the mass and velocity of the projectile, respectively. Solving (1), (2), (3), and (4) by using the Runge–Kutta method, all parameters describing the characteristics of the coilgun are obtained.

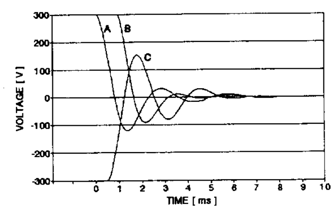
Fig. 3 shows the experimental system. The capacitance per phase is 760 μF. The driving coils have 48 turns. The barrel is made of a bakelite tube and its thickness is 1.2 mm. Three shunt resistors are used for measuring currents and a photo diode for measuring velocity. The firing sequence becomes A, $-$C, B and the firing interval between each switch actuation is 60°.

TABLE I
Specification of the Model used in the Simulation and Experiment

Coil turns of driving coils	48 turns
Thickness of driving coils	6 mm
Length of driving coils	25 mm
Inner diameter of driving coils	61.4 mm
Gap between each coil	2.0 mm
Length of projectile	100 mm
Thickness of projectile	1.6 mm
Outer diameter of projectile	58.4 mm
Material of projectile	Aluminum
Mass of projectile	76 g
Conductivity	2.861×10^7 [S/m]



(a)



(b)

Fig. 4. (a) Voltage waves (experiment). (b) Voltage waves (simulation).

IV. Numerical and Experimental Results

To verify the validity of the simulation program, the numerical results are compared with the experimental values for several cases. The specifications of the model used in the analysis and the experiment are shown in Table I. The numbers of the driving coils and the effective coils of the sleeve are 6 and 20, respectively. The charging voltage of the capacitor bank and the capacitance per phase are 300 V and 760 μF, respectively, and the firing interval is 60° (450 μs).

Figs. 4 and 5 show the waves of the voltage and current of the driving coils respectively. It is noted that the numerical and experimental results show little difference between them.

Figs. 6, 7, 8, and 9 show the comparisons between the numerical and experimental results for the various charging voltages, capacitances, firing intervals, and initial positions of the projectile. At the starting point, the charging

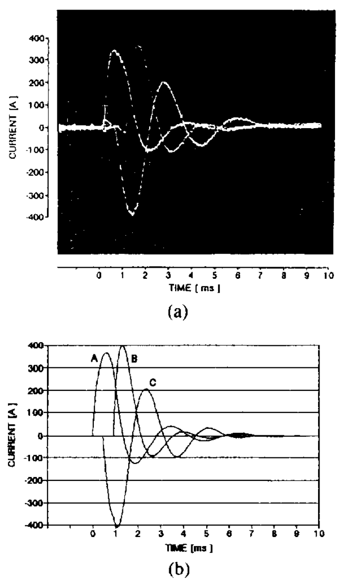


Fig. 5. (a) Current waves (experiment). (b) Current waves (simulation).

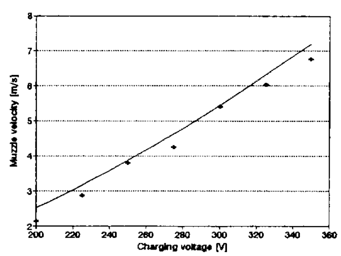


Fig. 6. Muzzle velocities versus charging voltages.

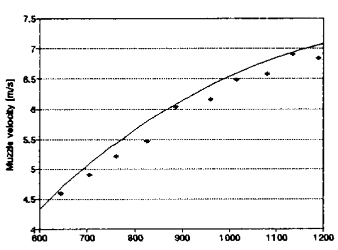


Fig. 7. Muzzle velocities versus capacitances.

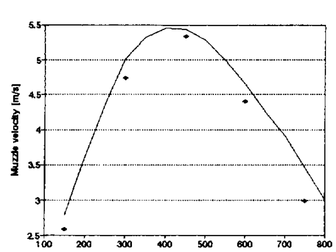


Fig. 8. Muzzle velocities versus firing intervals.

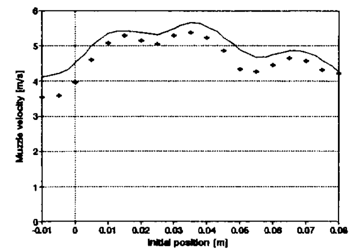


Fig. 9. Muzzle velocities versus initial positions of projectile.

voltage, capacitance and firing interval are 300 V, 760 μF and 60° (450 μs), respectively.

In these figures, all the experimental values are slightly smaller than the numerical results. One reason is that friction between the barrel and the sleeve may have been present, but was not considered in the simulation.

V. Optimal Design by Genetic Algorithm

The barrel length, gap size between two coils, coil turns, firing interval and initial projectile position are taken as design variables which are the same ones as the input variables of the simulation program. The five design variables are shown in Fig. 10. The length l_c and the thickness t_c of each coil are calculated from the following equations,

$$l_c = \frac{l_b - 5 \times l_i}{6}, \tag{5}$$

$$t_c = \frac{S_c \times n}{l_c}, \tag{6}$$

where l_b is the barrel length, l_i the gap size between two coils, n the number of coil turns and S_c the cross sectional area of the coil as shown in Fig. 10.

Since the design variables interact with each other in the course of the design, it is very difficult to obtain optimum results by using existing methods. Also a global optimization cannot be reached easily with deterministic methods, because the problem has many local optima. To get around these difficulties, a numerical simulation method and the genetic algorithm for optimization are used. The genetic algorithm is based on evolution through generations. The evolution consists of three steps: reproduction, crossover and mutation [11], [12]. In this paper the "biased roulette wheel spinning" method for reproduction is used and a method similar to the uniform crossover method for crossover. The probability of mutation is given by

$$(\text{mutation probability}) = 0.0047 + (\text{generation}) \times 0.002. \tag{7}$$

Table II shows the optimal design results of the coilgun. For given charging voltage, capacitance and the dimensions of the projectile, the barrel length, gap size between two coils, coil turns, firing interval and initial

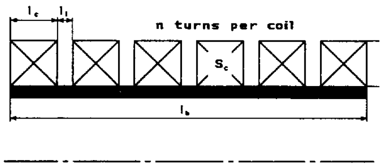


Fig. 10. Design variables for the coilgun.

TABLE II
RESULTS OF OPTIMAL DESIGN FOR 1 SECTION COILGUN

Aluminum projectile	length [mm]	100
	thickness [mm]	1.6
	outer diameter [mm]	58.4
	mass [g]	76
	initial position [mm]	14.66
Driving coils	turns	36
	thickness [mm]	3.48
	length [mm]	20.715
	gap size [mm]	2.572
	inner diameter [mm]	61.4
capacitance per phase [μF]		760
charging voltage [V]		600
firing interval [μs]		363.64
muzzle velocity [m/s]		18.57

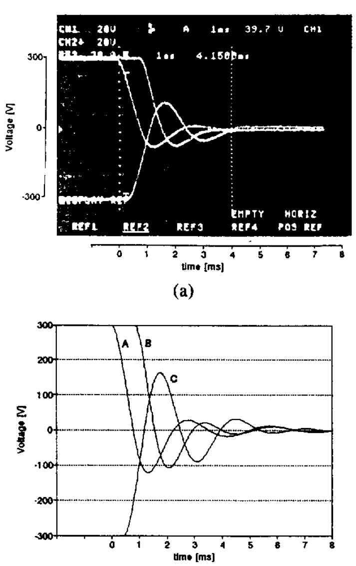


Fig. 11. (a) Driving coil voltage waves of optimized coilgun (experiment). (b) Driving coil voltage waves of optimized coilgun (simulation).

position of projectile are determined for a maximum muzzle velocity.

Figs. 11 and 12 show the voltage and current waves of the driving coils obtained by experiment and simulation. Figs. 13, 14 and 15 show the positions, velocities and accelerations of the projectile, respectively.

The coilgun in [4] has been designed by the approximate equations, and the muzzle velocity of the projectile is 3.5 m/s. When the coilgun is designed by the proposed

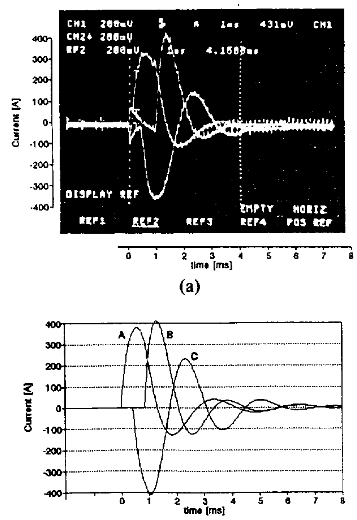


Fig. 12. (a) Driving coil current waves of optimized coilgun (experiment). (b) Driving coil current waves of optimized coilgun (simulation).

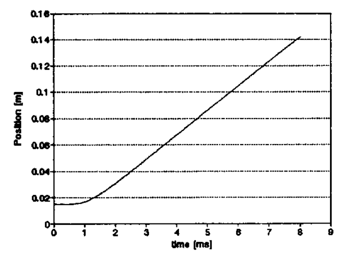


Fig. 13. Projectile positions of optimized coilgun.

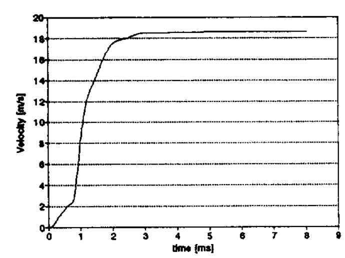


Fig. 14. Projectile velocities of optimized coilgun.

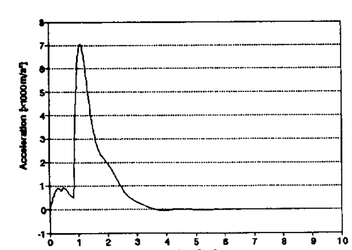


Fig. 15. Projectile acceleration of optimized coilgun.

algorithm with the same charging voltage and capacitance used in reference [4], the muzzle velocity becomes 4.7 m/s. From these results, it is seen that the proposed algorithm gives a better performance of the coilgun with respect to the muzzle velocity.

VI. Conclusion

This paper describes a launch simulation and an optimal design for the capacitor-driven inductive coilgun. For the simulation an equivalent circuit is used. The voltage and current waves of the driving coils are obtained by solving the circuit equations. The relationship between the muzzle velocity and the charging voltage, capacitance, firing interval, and initial position of projectile is obtained. The usefulness of the simulation program is proven by the comparisons between the numerical and experimental results; the simulation results are in good agreement with the experimental results. For the optimal design of the coilgun, the optimization is achieved by using a genetic algorithm. From the comparisons between the results obtained by the proposed algorithm and those by other algorithms, it can be concluded that the optimal design method employing the genetic algorithm is more powerful than other existing methods. In future work, the proposed method will be applied to the design of a multistage coilgun.

Acknowledgment

H. K. Jung is grateful to Prof. Z. Zabar, Prof. E. Levi, Prof. L. Birenbaum, and Dr. J. L. He for the chance to gain experience with the polyphase induction coilgun during his stay at Polytechnic University.

References

[1] H. Kolm and P. Mongeau, "Basic principles of coaxial launch technology," *IEEE Trans. Magn.*, vol. 20, no. 2, pp. 227–230, 1984.
[2] H. D. Fair, P. Coose, C. P. Meinel, and D. A. Tidmin, "Electromagnetic earth-to-space launch," *IEEE Trans. Magn.*, vol. 25, no. 1, pp. 9–16, 1989.
[3] H. Mark, "Electromagnetic launch technology: The promise and the problems," *IEEE Trans. Magn.*, vol. 25, no. 1, pp. 17–19, 1989.
[4] J. He, E. Levi, Z. Zabar, and L. Birenbaum, "Concerning the design of capacitively driven induction coil guns," *IEEE Trans. Plasma Sci.*, vol. 17, no. 3, pp. 429–438, 1989.
[5] Z. Zabar, Y. Naot, L. Birenbaum, E. Levi, and P. N. Joshi, "Design and power conditioning for the coil-gun," *IEEE Trans. Magn.*, vol. 25, no. 1, pp. 627–631, 1989.
[6] D. G. Elliott, "Traveling-wave induction launchers," *IEEE Trans. Magn.*, vol. 25, no. 1, pp. 159–163, 1989.
[7] K. Mckinney and P. Mongeau, "Multiple stage pulsed induction acceleration," *IEEE Trans. Magn.*, vol. 20, no. 2, pp. 239–242, 1984.
[8] Z. Zabar, X. N. Lu, J. L. He, L. Birenbaum, E. Levi, S. B. Kuznetsov, and M. D. Nahemow, "Test results for three prototype models of a linear induction launcher," *IEEE Trans. Magn.*, vol. 27, no. 1, pp. 558–562, 1991.
[9] J. L. He, Z. Zabar, E. Levi, and L. Birenbaum, "Transient performance of linear induction launchers fed by generators and by capacitor banks," *IEEE Trans. Magn.*, vol. 27, no. 1, pp. 585–590, 1991.
[10] T. H. Fawzi and P. E. Burke, "The accurate computation of self and mutual inductance of circular coils," *IEEE Trans. Power Appar. Syst.*, vol. 97, no. 2, pp. 464–468, 1978.
[11] D. E. Goldberg, *Genetic Algorithms*, Addison-Wesley, 1989.
[12] L. Davis, *Handbook of Genetic Algorithms*, New York: Van Nostrand Reinhold, 1991.

Seog-Whan Kim was born in Seoul, Korea in 1964. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Seoul National University, Seoul Korea in 1986, 1988 and 1993, respectively. He is presently a researcher in the Department of Electrical Engineering Seoul National University, Seoul Korea.

His current research interest includes optimal design of electrical machinery, electromagnetic missiles (coilgun) and superconducting generator.

Hyun-Kyo Jung was born in Jinboo, Korea in 1955. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Seoul National University, Seoul Korea in 1979, 1981, and 1984, respectively.

In 1985, he joined the faculty of the Department of Electrical Engineering, Kangweon National University, Chuncheon, Korea, where he is presently an associate professor. From 1987 to 1989, he was a Visiting Scholar in Department of EE/CS, Polytechnic University, New York, NY.

His current research interest includes numerical analysis in electromagnetic, wave propagation in difficult environments and electromechanical energy conversion.

Song-yop Hahn was born in Bucheon, Korea in 1939. He received the B.S. and M.S. degrees in electrical engineering from Seoul National University, Seoul Korea in 1963 and 1967, respectively, and Ph.D. degree from Lorraine National Polytechnic Institute, Nancy, France, in 1979.

Since 1968, he has been with Department of Electrical Engineering, Seoul National University, where he is presently a professor. In 1985 he was a visiting professor in Grenoble National Polytechnic Institute, Grenoble, France.

His research includes numerical analysis in electromagnetics, optimizing design of electrical machinery and superconducting generator.