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Projectile velocity control on coilgun using genetic algorithms

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ABSTRACT

Multistage Coilgun is an electromagnetic coil composed of more than one coil so that can throw a projectile. The velocity of the projectile coming out of the tube must be controlled. The mechanism can be done by a multistage coilgun design that has a varying number of turns. Each coil that coincides with one another is wrapped separately. The motion of projectile following the velocity profile is perfomed by designing a multistage coil in different layer number based on the energy needed, and therefore the coil is more efficient. Furthermore, the velocity of the projectile is controlled by controlling the current injected to the coil using the Genetic Algorithm method. A prototype of a multistage coilgun system with the proposed coil variation is built in this work. The test is carried out 7 times with an average final velocity of the projectile of 29,89 m/s. While the results of the numerical simulation are 32,63 m/s. Testing error compared to simulation is 9,15%.

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1. INTRODUCTION

Coilgun is a projectile launcher using an electromagnetic system. It converts the electrical energy into kinetic energy. In implementation, it also can be used to launch a small satellite into the space. The structure of coilgun is constructed in single-stage or multi-stage based on its coils arrangement. Multistage coil consists of several coils and is superior to the single stage type. Many research developed electromagnetic launcher coil gun system with multi-stage electromagnetic coils and each stage has the same coil shape [1-4]. They control the current injection of each coil alternately and unfortunately motion of the projectile is not controlled. The projectile transfer rate can be controlled by variation of the coil [5]. Motion of the projectile inside the tube is controlled by changing the number of turns or number of layers on each coil. The motion of the projectile is affected by the difference magnetic size field in each coil [6-8].

In this paper, the motion of projectile inside the tube is controlled by adjusting the current injection and varying the number of turns or number of layers on each coil. The desired velocity of projectile inside the tube is designed by considering the energy requirement and current injection [9, 10]. At the beginning of the motion projectile has a low velocity so it requires small energy. Then the velocity increases so that it requires more energy. The novelty of the construction in this paper is that the form of coils is different in stages because it adjusts the amount of energy needed. Furthermore, a control strategy should be designed to control the current injection on each stage coil and therefore projectile moves following the desired trajectory.

The genetic algorithm method is offered to regulate the injection current of each coil simultaneously in order to control the motion of projectiles [11-14]. The injection current arrangement uses PWM with changes in the duty cycle [15-17]. This is done so that the projectile gets the magnetic force as needed to reach the expected velocity profile [18-20]. The results of controlling the motion of these projectiles can be used as a reference for designing a weapon in a combat vehicle because the coilgun projectile is easily made using iron so it does not depend on the factory.

2. RESEARCH METHOD

2.1. Coil design

To design a multistage coilgun that can control a projectile, the velocity profile reference must be determined first. While the other parameters specified are the number of stage coils and projectile dimensions. In this study the stage coil arrangement was determined as many as 6 coils with coil forming wires using the AWG # 10 standard with a diameter of 2,58 mm and arranged coincidentally. The projectile is determined by 39 mm length and 5,45 mm diameter. The motion of the projectile along the tube has a velocity profile shown in Figure 1. The order of 6 polynomial interpolation method is used to obtain the equation of the velocity profile which is used as an objective function and shown by equation (1)

$$v(t) = 1{,}5.10^{-7}.t^6 - 9.10^{-6}.t^5 + 3.10^{-4}.t^4 - 2{,}9.10^{-3}.t^3 + 3{,}04.10^{-2}.t^2 - 9{,}7.10^{-2}.t + 1 \quad (1)$$

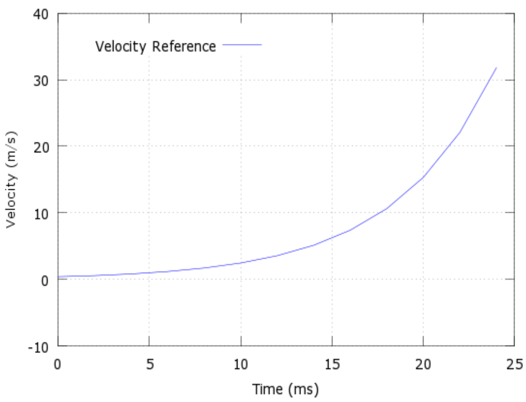

Figure 1. Velocity profile

The distance profile is obtained by integrating in equation (2) as a function of time.

$$x(t) = \int v(t).dt \quad (2)$$

From the desired velocity profile given in Figure 1 and utilizing equation (2), the farthest distance traveled for 24 ms is x (24 ms) = 160.17 mm. Projectile mileage is used as the basis for determining the sixth coil length. As each coil is determined to have the same length, hence calculation of length and number of turns of each coil are as follow:

$$Length\ of\ coil = \frac{160{,}17}{6} = 26{,}695\ mm$$

$$Turn\ per\ layer = \frac{26{,}695}{2{,}588} = 10{,}315 \approx 11$$

As the number of turns per coil are 11 turns, while the distance between coils coincides (zero), so the length of the coil is:

$$Length\ coil = 11\ x\ 2{,}588 = 28{,}468\ mm$$

The motion of the projectile as far as x requires the force at each point that forms a force profile by inferring the velocity profile and calculating the projectile mass according to (3)

$$F(t) = m.a(t)$$
$$F(t) = m.\frac{dv}{dt} \quad (3)$$

The acceleration experienced by projectiles at 24 ms is $a(24) = 2{,}79$ m/s^2. The projectiles used are cylindrical made of ferromagnetic material with a density of 7800 kg/m3. Calculation of projectile volume and mass:

$$V_p = l.\pi.{r_p}^2$$
$$= 9{,}039.10^{-7}m^3$$

$$m = \rho.V_p$$
$$= 0{,}07093\ kg$$

The profile of force affecting the projectile motion is derived based on the velocity profile and friction. The friction occurs due to the gravitational force in each position and is calculated using (4)

$$F_{friction} = m.g.\sin\vartheta + m.g.\cos\vartheta\ .coefficient\ of\ friction \quad (4)$$

The force required to move the projectile is the sum of the reference force and friction. The profile of force is used as input for calculating the magnetic flux that must be generated by the six coils. To simplify the calculation, the distance is divided into 6 areas, as shown in Figure 2, as follows:

a. Area 1 is the stationary position to the center of the coil 1
b. Area 2 is the middle of coil 1 to center coil 2
c. Area 3 is the middle of coil 2 to the middle of coil 3
d. Area 4 is the center of coil 3 to the center of coil 4
e. Area 5 is the center of coil 4 to the center of coil 5
f. Area 6 is the center of coil 5 to center of coil 6

Each area is used for calculating the maximum energy needed by using equation (5), as a function of distance.

$$E = \int F(x).dx \quad (5)$$

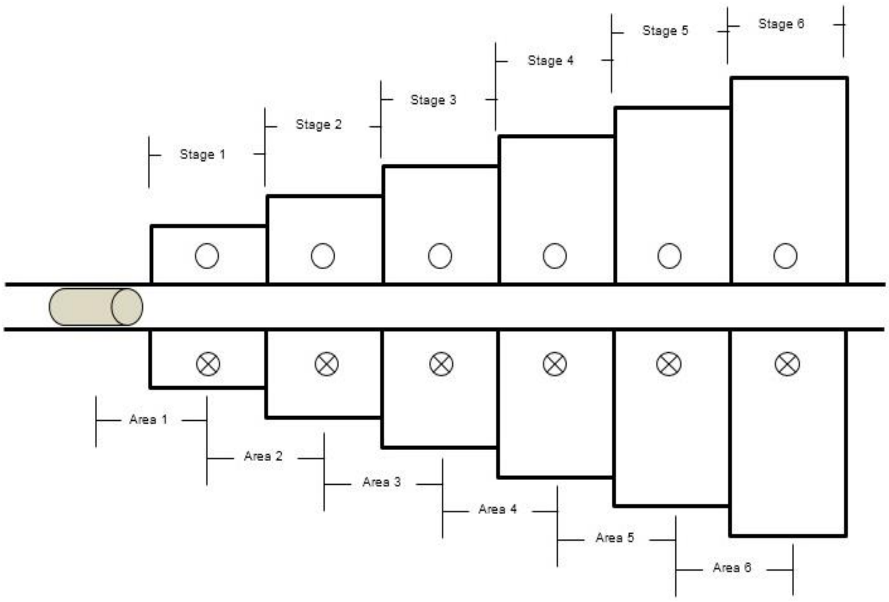

Figure 2. Coil Area

The energy calculation is used to determine the number of layers that will be used in the six coils. By consodering the coil parameters and maximum current of the conductor, the number of layer for each coil can be calculated using (6).

$$I_{max} = \sqrt{\frac{2.E.{D_k}^2}{\mu_0.A.n^2}} \quad (6)$$

While the wire length is calculated using (7)

$$P_{kn} = \pi.T_{PL}.(n.D_{L1} + (n^2 - n).D_k) \quad (7)$$

P_{kn} is the length of the wire, T_{PL} is the number of turns per layer, n is the number of layers, D_{L1} is the winding diameter in layer 1, A is the cross-sectional area of the wire and D_k is the diameter of the wire used to form the coil. The coil design specifications are shown in Table 1.

Table 1. Specification Coils.

Specification	Coil 1	Coil 2	Coil 3	Coil 4	Coil 5	Coil 6
Turn per Layer	13	26	37	39	51	56
Layer	28.47	28.47	28.47	28.47	28.47	28.47
Wire Length (mm)	16.41	63.04	126.10	132.90	237.63	285.96
Energy Max (J)	0.075	0.27	0.58	1.07	1.73	2.72
Current Max (A)	330	385	990	1100	1100	1100
Voltage Max (V)	11	44	247	504	802	1244

2.2. Genetic algorithms

Furthermore, based on the energy profile required in each coil, the controller is designed for providing the energy needed by controlling the enjected electric current. The genetic algorithm is utilized in this work for controlling the electric current by using PWM signal. The objective function used is a velocity profile that follows a geometric sequence, which is proportional to energy needed. To move a projectile in the tube following the velocity profile, all coils must be simultaneously injected. To find the sequence of duty cycles that produce the best velocity close to the reference, the Linear Rank Selection (LRS) method is used. To get better results, the selection with the best duty cycle are encoded into binner numbers which are then carried out uniformly in the crossover process, and therefore the variation of the new duty cycle is obtained. The mutation process is then carried out to obtain the next generation and form a new population duty cycle. This process continues until a minimum error [21].

2.3. Procedure of genetic algorithms

Genetic Algorithms is applied by limiting into 200 generations in a period. The Process of Genetic Algorithms takes place from the 1st to the 12th period which each generation produces a duty cycle value. Setting injection currents by changing the duty cyle encoded in a binary number 6x8 bits, so that each coil is encoded into 8 bits. Changes in duty cyle are carried out by trial and error 50 times and collected in a population. Each change in duty cycle is used as input for calculating projectile velocity. The results of velocity calculations are compared with the velocity profile used as reference and produce a certain error value. This process continues until a minimum error is reached with a maximum limit of 200 generations. The flow chart of the Genetic Algorithms method can be seen in Figure 3.

3. RESULTS AND ANALYSIS

The Genetic Algorithm method is used to regulate 6 current injection duty cycles according to the velocity profile requirements. The iteration of duty cycle results is shown in Table 2. The results of the duty cycle settings for the voltage and current for coil 1 in period 1 to 12 are shown in Figure 4-9. Deviation occurs in each injection period, this is due to a non-continuous injection system, ie. PWM injection. Whereas the velocity profile produced from the simulation is shown in Figure 10. After the simulation, we made a prototype according to the design and tested it. The coil and tube used for testing is shown in Figure 11. The test is carried out by assembling all the coils and connecting with the voltage generator.

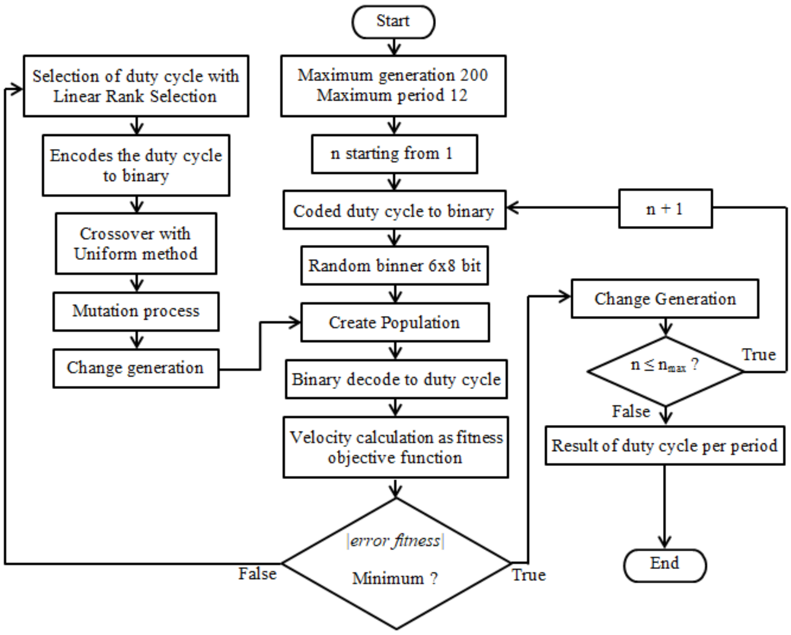

Figure 3. Folwchart genetic algorithm

Table 2. Iteration of Duty Cycle

Period	Coil 1	Coil 2	Coil 3	Coil 4	Coil 5	Coil 6
1	31.37	43.92	66.27	81.57	81.96	75.68
2	18.43	28.23	16.08	48.63	19.21	66.62
3	26.25	84.18	9.41	17.60	57.64	81.97
4	71.76	3.53	82.74	89.08	85.58	37.17
5	17.25	53.55	95.56	78.33	93.72	96.08
6	89.29	61.51	99.12	97.54	90.58	84.34
7	23.52	34.98	87.84	85.88	99.78	84.70
8	30.68	12.15	95.47	99.28	82.16	90.98
9	63.92	98.12	96.71	70.21	83.52	92.50
10	62.84	94.18	92.78	67.41	84.41	92.94
11	73.33	90.57	90.66	90.95	88.25	94.56
12	27.34	19.21	1.96	11.20	10.46	64.47

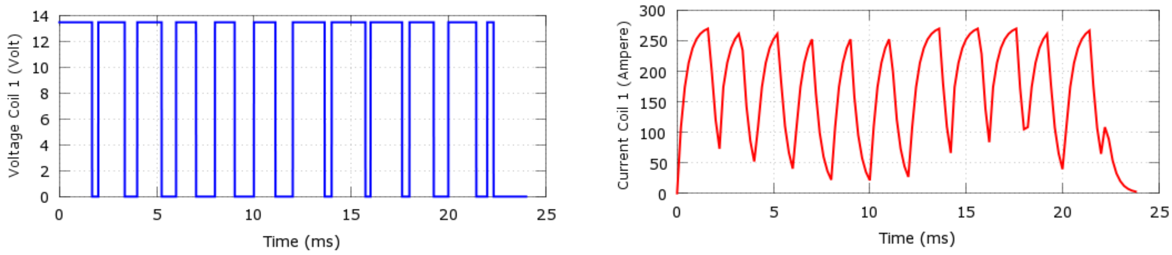

Figure 4. Voltage and current coil 1

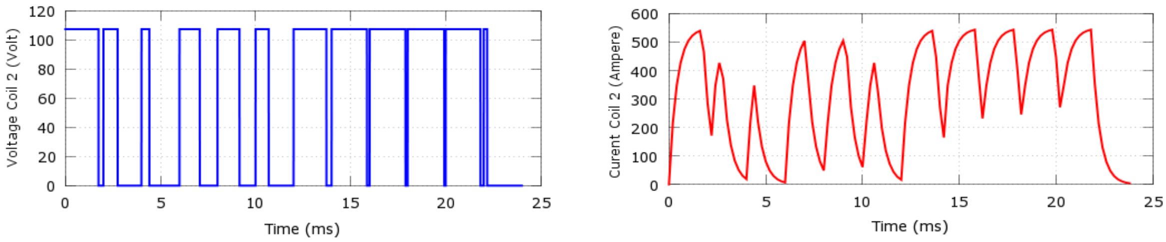

Figure 5. Voltage and current coil 2

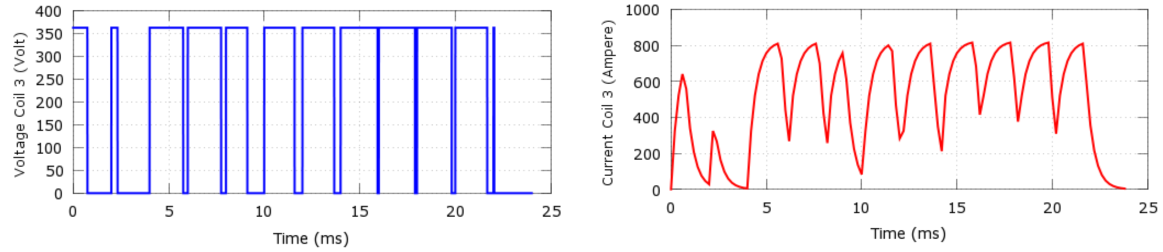

Figure 6. Voltage and current coil 3

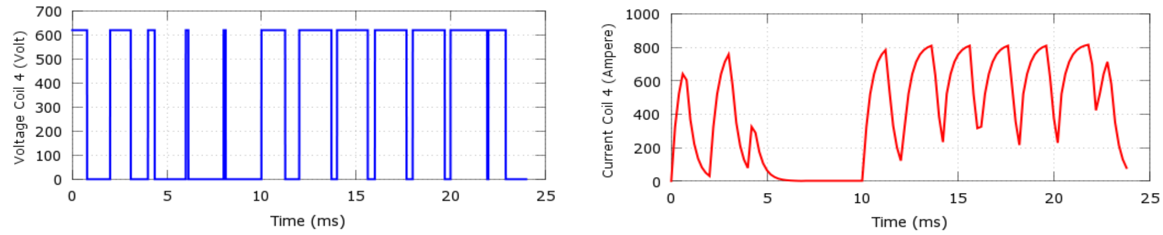

Figure 7. Voltage and current coil 4

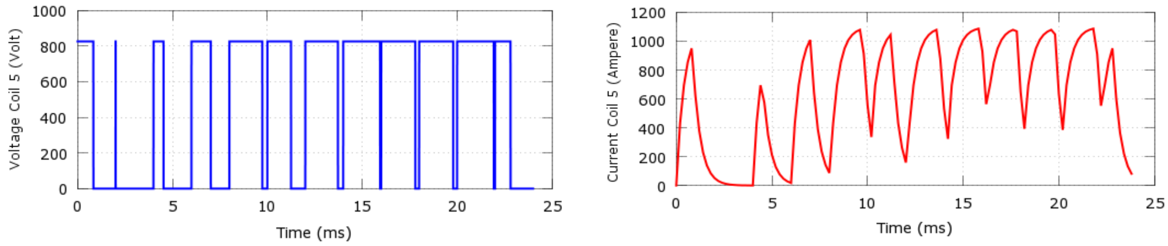

Figure 8. Voltage and current coil 5

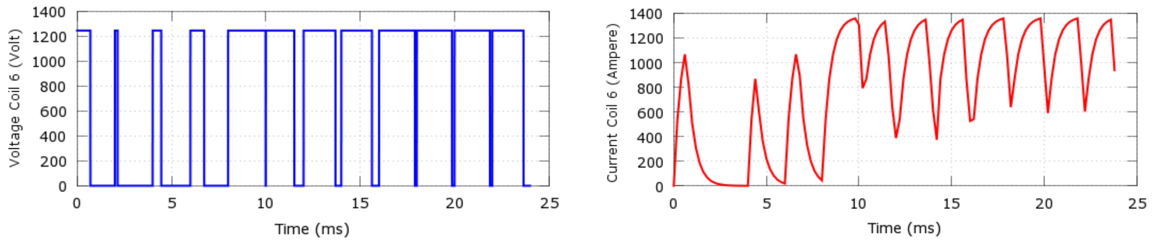

Figure 9. Voltage and current coil 6

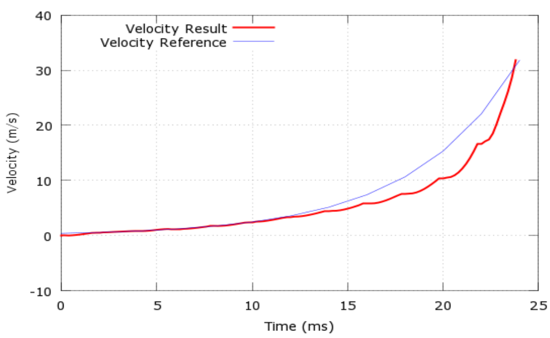

Figure 10. Velocity result

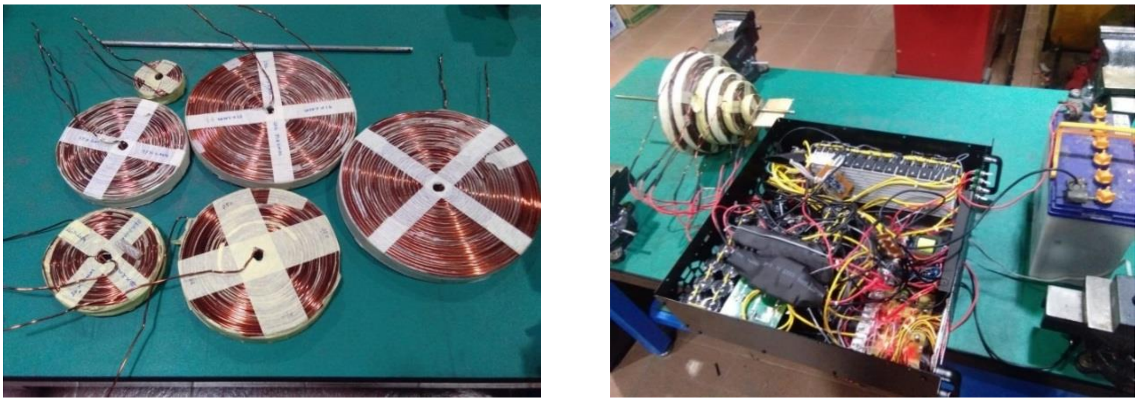

Figure 11. Coilgun test

Velocity measurement is done by placing 2 infrared sensors at the end of the tube. Sensor placement by giving 2 holes on the tube as far as 100mm. Hole 1 is marked with T1 and hole 2 is marked with T2 to measure the time it takes for the projectile to move from T1 to T2. Projectile velocity is calculated based on the difference in time shown on the two sensors. Each experiment requires a capacitor recharge time to increase the voltage between 4 to 5 minutes. The results of velocity measurements are shown in Table 3.

Table 3. Velocity measurements

Period	$T_1 - T_2$ (mm)	Measurements Result	
		Distance (mm)	Velodity (m/s)
1	3.29	100	30.40
2	3.46	100	28.90
3	3.06	100	32.68
4	3.76	100	26.60
5	3.31	100	30.21
6	3.47	100	28.20
7	3.16	100	31.65

4. CONCLUSION

A new method for designing a multistage coilgun is proposed in this work. The coil is designed by considering the profile of velocity reference and energy requirements. Therefore, the design of coil is more efficient. Furthermore, for controlling the motion of projectile inside the tube, a genetic algorithm is proposed. The effectiveness of the proposed method is evaluated in simulation and experimentally. The simulation that has been done shows that there is a match between the reference velocity profile and the design velocity profile. We built a prototype and tested a multistage coilgun system with the proposed coil variation. The test is carried out 7 times with an average final velocity of the projectile of 29.89 m/s. While the results of the numerical simulation are 32.63 m / s. The test error compared to the simulation is 9.15%. This high level of error occurs because of the coil density in each coil which affects changes in the magnetic field and thermal energy of the coil. We hope to conduct additional studies to improve energy efficiency and reduce errors because each experiment takes a long time to recharge capacitor when increasing voltage.

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