Optimization of Electromagnetic Railgun and Projectile's Trajectory by Genetic Algorithm

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ABSTRACT:
In this paper, the optimization of the electromagnetic railgun and its projectile path is proposed. The circuit model is used to optimize and simulate the elec- tromagnetic railgun, in which the equivalent circuit of the railgun is extracted. Then the differential equations expressing the physics governing the system are obtained. Using the projectile path equations and simulate them in MATLAB, the output of the simulation of the electromagnetic railgun and its projectile path in MATLAB software has been analyzed. The main advantage of the mod- els used is that they can be used in matters of sensitivity and optimization due to their high speed. Based on the obtained outputs of electromagnetic railgun and projectile path, the cost function is presented, and then the effective pa- rameters of models are optimized using the genetic algorithm. The results show that the losses and costs are drastically reduced for the same purposes, and the waste of costs and energy is prevented.

KEYWORDS: Railgun, Genetic Algorithm, Modeling, Simulink Simulation, Optimization.

1. INTRODUCTION

Electromagnetic launchers have recently attracted the attention of many researchers due to their many advantages, and many military organs of powerful countries have made significant investments in this technology.

In recent years, much research has been done on different quantities of rail guns. In [1], inductance gradient and density calculations have been done numerically and compared with laboratory values. Also, in [2, 3, 4], researchers investigate the effect of changing geometry and structure of rails and armatures on the flow gradient and parameters of the rail gun. In [5], a reinforced rail gun is introduced by adding another pair of rails between the rails and compared to a simple rail gun.

In references such as [6, 7], the authors have studied the pulse power supply of the rail gun and have also proposed practical examples. [8] Has investigated the effect of rail and armature material on the performance of rail guns and has shown that the shape of the inner grooves of the rail is effective in deforming parts with high temperatures.

There are two methods for modeling electromagnetic railguns: 1) Circuit model 2) Finite element method (FEM) based model. Although FEM-based models exhibit similar behavior to real systems, they are often very complex and unsuitable for optimization and sensitivity analysis purposes [9, 10, 11]. Modeling of electromagnetic rail guns is mainly done for three purposes. 1)

Obtaining accurate information about the behavior of specific components of electromagnetic rail guns such as rails; 2) Predict the overall performance of electromagnetic rail test tests 3) Using the model for optimization and performance improvement purposes [12]. On the other hand, Circuit models are more explicit and suitable for experimental analysis and evaluation of electromagnetic railgun performance [13, 14]. [15] is proposes intelligent estimation method for gradient inductance. In a study involving a nonlinear circuit model [16], the variable resistance is considered in series and the variable inductance, where both change based on the projectile position. In the thesis [17], the circuit model has been presented, and the optimization of the electromagnetic railgun has been discussed through the fmincon MATLAB optimization command. In the reference[18], the circuit model is presented much faster than the numerical method. Circuit model simulation results confirmed the precision of the model as they are very near to the experimental ones; this circuit model is also the basis of our circuit model.

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This paper is organized as follows. Section II presents the governing equations and circuit model, and projectile trajectory. Section III proposes optimization methods and cost function, and genetic algorithm. IV discusses the simulation results and optimization result. Finally, the conclusion is presented in Section V.

2. MODELING

In this section, modeling and equation of electromagnetic railgun and projectile path are derived.

2.1. Circuit model of electromagnetic railgun

In this section, one of the units of this power supply is considered as the excitation circuit. This power supply is part of a real power supply that is mentioned in reference [7], but note that, in fact, the total energy of the case need arises from the sum of many of these units. The proposed circuit model in Fig. 1 shows a rail gun connected to the excitation circuit at points a and b. In this form, capacitor C with initial voltage V0 acts as a power supply for the rail gun, and inductor L0 is used to prevent currents created when the switch is connected and is used to protect the capacitor. Also, a parallel resistor is located at the end of the rail; when the armature comes out, it is used to close the circuit and keep the inductor current L0 constant. However, this parallel resistance at the end of the rail is not shown in Fig. 1.

The equivalent circuit model of the railgun, as shown in Fig. 2, and the final differential equation for the electrical section of the electromagnetic railgun is:

$$\begin{cases} \frac{d^2 i(t)}{dt^2}(L_0 + L'x(t)) + \frac{di(t)}{dt}(R_0 + R'x(t) + 2L'\frac{dx(t)}{dt}) \\ \qquad + i(t)(\frac{1}{C} + R'\frac{dx(t)}{dt} + L'\frac{d^2 x(t)}{dt^2}) = 0 \\ \qquad \frac{di(0)}{dt} = \frac{V_0}{L_0 + L'x_0}, i = (0) = 0 \end{cases} \tag{1}$$

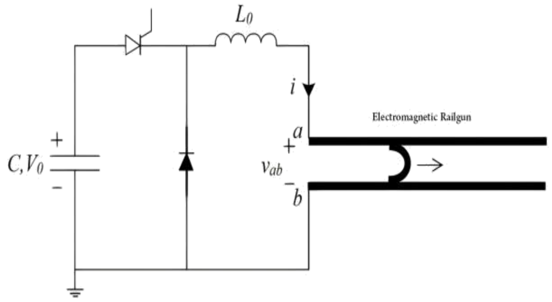

Fig. 1. A circuit model of railgun.

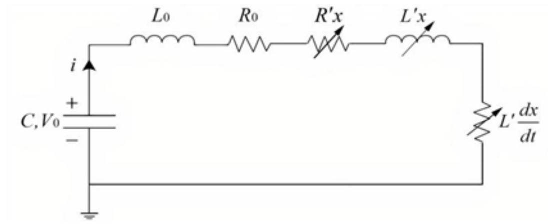

Fig. 2. A equivalent circuit model of railgun [18].

the geometrical shape as shown in Fig. 3 and inductance gradient and resistance gradient depends on the rail's geometrical shape and material and be calculated as [19]:

$$R' = \frac{2}{\sigma(w \times h)} \tag{2}$$

$$L' = \frac{10^{-6}}{0.5986\frac{h}{s} + 0.9683\frac{h}{s+2w} + 4.3157\frac{1}{Ln(\frac{4(s+w)}{w})} - 0.7831}$$

Where is the rail's conductivity. Based on the fundamentals of electromechanical energy interchange and Newton's second law, the mechanical part of the electromagnetic railgun is:

$$\begin{cases} \frac{d^2 x(t)}{dt^2} = \frac{L'}{2m} i^2(t) \\ \frac{dx(0)}{dt} = v_0, \qquad x(0) = x_0 \end{cases} \tag{3}$$

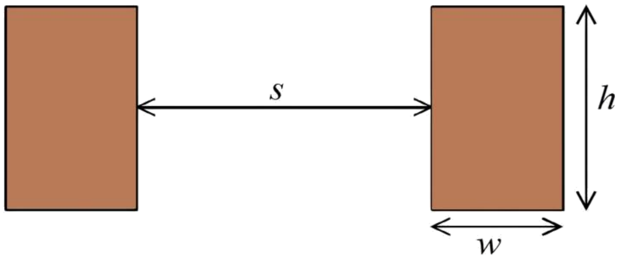

Fig. 3. Geometrical shape of railgun

The complete model of the electromagnetic railgun is presented as follows:

$$\begin{cases} \frac{d^2 i(t)}{dt^2}(L_0 + L'x(t)) + \frac{di(t)}{dt}(R_0 + R'x(t) + 2L'\frac{dx(t)}{dt}) \\ \qquad + i(t)(\frac{1}{C} + R'\frac{dx(t)}{dt} + L'\frac{d^2 x(t)}{dt^2}) = 0 \\ \qquad \frac{d^2 x(t)}{dt^2} = \frac{L'}{2m} i^2(t) \\ \qquad \frac{di(0)}{dt} = \frac{V_0}{L_0 + L'x_0}, \qquad i = (0) = 0 \\ \qquad \frac{dx(0)}{dt} = v_0, \qquad x(0) = x_0 \end{cases} \tag{4}$$

2.2. Projectile path

After the projectile lives rail's endpoint, air drag is one of the principal factors changing the force operating on the projectile. Therefore, forces in the y-axis and x-axis directions are calculated by taking air drag into account, and the following equations can give them:

$$\begin{aligned} F_x &= -F_{dx} \\ F_y &= -F_{dy} \end{aligned} \quad (5)$$

where, Fdy and Fdx are the force acting on the projectile in y-axis and x-axis direction due to air drag, which can be further expanded as follow:

$$\begin{aligned} F_{d\,x} &= ma_{dx} \\ F_{d\,y} &= ma_{dy} + mg \end{aligned} \quad (6)$$

therefor,

$$\begin{aligned} a_{d\,x} &= \frac{F_{dx}}{m} = \frac{AC_{d\rho}(v_0^2 \cos\theta)}{2m} \\ a_{d\,y} &= \frac{AC_{d\rho}(v_0^2 \sin\theta)}{2m} \end{aligned} \quad (7)$$

Here, both and v0 is dependent on vx and vy based on:

$$\begin{aligned} \theta &= \tan^{-1}(\frac{v_y}{v_x}) \\ V_0 &= \sqrt{V_x^2 + V_y^2} \end{aligned} \quad (8)$$

Substituting Eq. 8 and Eq. 7 into Eq. 6

$$F_{dy} = m(\frac{AC_{d\rho}(v_0^2 \sin(\tan^{-1}(\frac{v_y}{v_x})))}{2m}) + mg \quad (9)$$

from Eq. 12 and Eq. 7,

$$\begin{aligned} \frac{dv_x}{dt} &= -\frac{AC_{d\rho}(v_0^2 \cos(\tan^{-1}(\frac{v_y}{v_x})))}{2m} \\ \frac{dv_y}{dt} &= -\frac{AC_{d\rho}(v_0^2 \sin(\tan^{-1}(\frac{v_y}{v_x})))}{2m} - g \end{aligned} \quad (10)$$

3. OPTIMIZATION

After obtaining the complete railgun and projectile path model, optimization was done to hit the target precisely with minimum losses. Some parameters have been investigated on the losses and the target point of the projectile. It has been observed that it is possible to increase the distance of the target point of the projectile by increasing and increasing the initial voltage. But, if the initial voltage increases, the losses are significantly increased, and the purpose is to reduce the losses;

For this paper, the optimization function consists of two parts. The first part is the square of the difference between the set target position and the achieved target position. An objective function is designed to reduce this error. Because of this part, after the optimization process, the projectile should hit the target location accurately. The second part of the optimization function includes the mean power loss term. Hence the cost function for optimization is defined as follows:

$$\begin{gathered} \min J \\ \theta, V_{init} \\ J = \underbrace{K_{t0}(x_{ref} - x_{end})^2}_{Target\ \ offset} + \underbrace{K_{Culoss}(mean(C_{uloss}))^2}_{loss} \end{gathered} \quad (11)$$

The value of Kto is considered very large because the importance of accurately target offset is very high, and the value of KCuloss is considered very small. In this research, a genetic algorithm (GA) is considered to optimize the objective function. The genetic algorithm (GA) solves both constrained and unconstrained optimization problems based on a natural selection method that mimics biological evolution. The algorithm frequently modifies a population of individual solutions. The genetic algorithm haphazardly selects individuals from the current population at each step and utilizes them as parents to produce the children for the next generation. Over successive generations, the population evolves toward an optimal solution.

4. SIMULATION RESULT

The electromagnetic railgun can now be simulated in MATLAB Simulink.

The specification of the simulated railgun and simulated projectile path are presented in table 1, 2. In this research, the armature is the same as the projectile the results of the basic railgun form have been examined, Fig. 4 shows the current changes over time as a system input. Due to the presence of an inductor to prevent the impulse current in the excitation circuit, the current increases from zero to maximum value. By converting stored capacitor energy capacitor into the kinetic energy of the armature, according to the capacitor voltage is reduced, the current is also reduced.

The amplitude of the current is large because all parameters of the railgun are also relatively large, and it has been observed that a 20 kg projectile is

Table 1. Specifications of the simulated railgun.

Parameter	definition	value
C	Capacitor bank capacity	12 F
m	Armature weight	20Kg
V0	Initial voltage of capacitor	7000 V
L0	-	1 H
R0	-	0.5m
x0	Initial position of projectile	0m
v0	Initial velocity of projectile	0 m/s
l	Rails length	12 m
w	Rails width	0.061 m
h	Rails height	0.135 m
s	Rails seperation	0.5 m

Table 2. Specifications of the simulated railgun.

Parameter	definition	value
g	Gravitational acceleration	9.8 m=s2
lpr	Projectile length	0.2 m
wpr	Projectile width	0.061 m
Cd	Projectile Drag coefficient	0.1
	Air density	1.255 Kg=m3
A	Projectile area	0.0122 m2

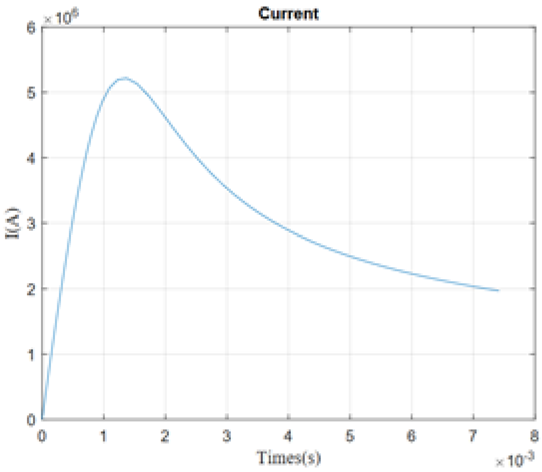

Fig. 4. Current

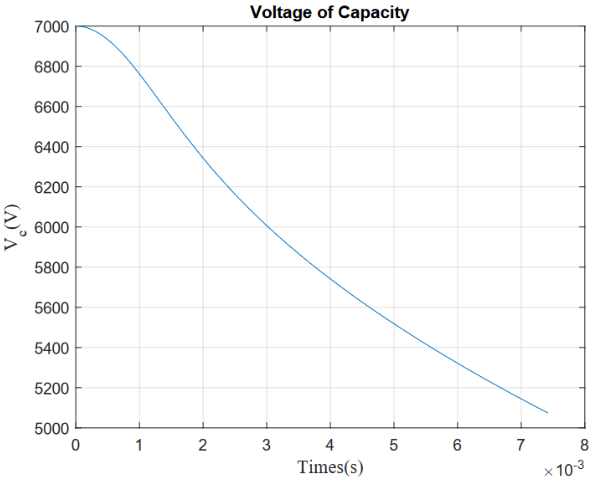

Fig. 5. Voltage of Capacity

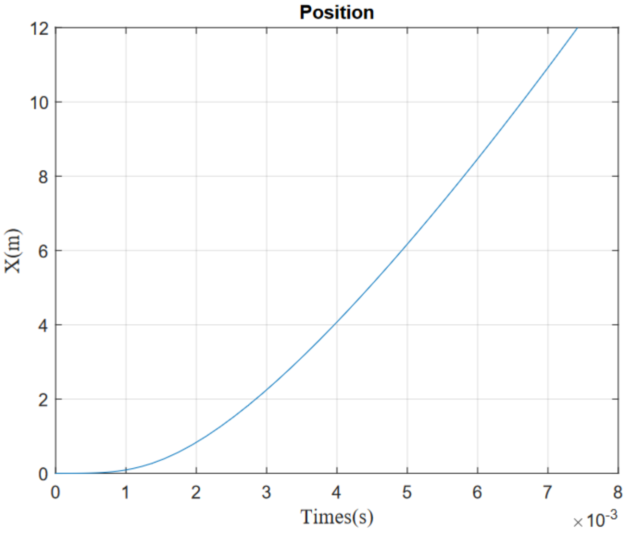

Fig. 6. Position of Armature

Fig. 6 shows the changes in armature position. It can be seen that the slope of the graph, which expresses speed, is increasing. The time it takes for the armature to come out of the end of the rail is about (s0.00744). As shown in Fig. 7, the arm velocity changes, starting at 0 (which is the initial velocity) and eventually reaching a projectile velocity of 2600 m / s.

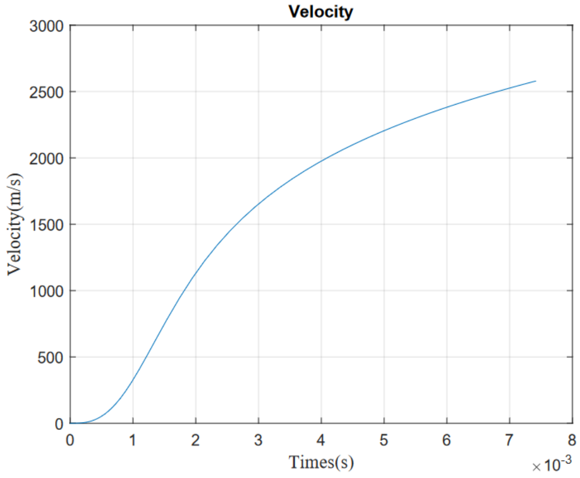

Fig. 7. Velocity.

Fig. 8 shows the changes in the force applied to the projectile. As shown in Fig. 9, according to the initial capacitor voltage and theta, the armature or projectile hit the target at a distance of 52,659 meters.

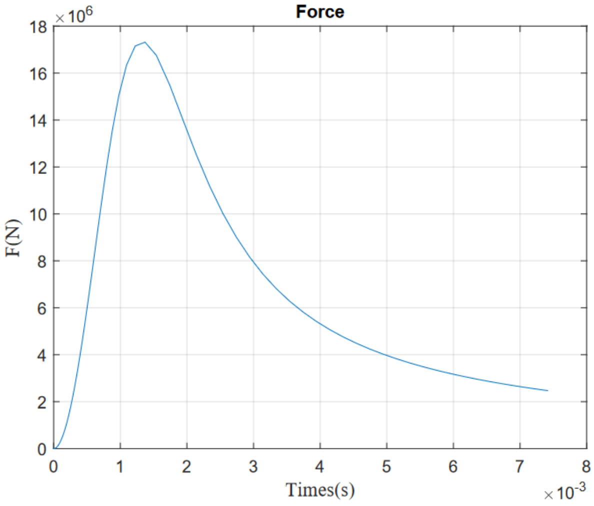

Fig. 8. Force.

For optimization is considered lower bound and upper bound for initial volt-age and that shows as follow:

$$
\begin{aligned}
&1 < \theta < 90 \\
&2000 < V_{init} < 10000
\end{aligned}
\quad (12)
$$

After optimizing the proposed objective function by genetic algorithm, the optimal values for the target have been obtained, and optimal values have been able to reduce the losses well. In Table 3, the optimized values and the comparison of losses for the two results are presented. As shown in Fig. 10, both values hit the same target with different paths and losses.

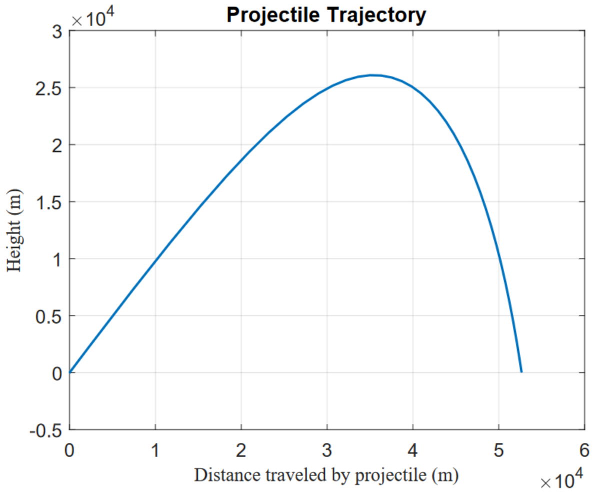

Fig. 9. Projectile path for not optimized path

Table 3. Optimization result.

Identification method	θ - V_{init}	CUloss
Not optimized values	45(deg) - 7000 v	$3.3950*10^9$w
Optimized values	30.4(deg) - 5450 v	$2.5208*10^9$w

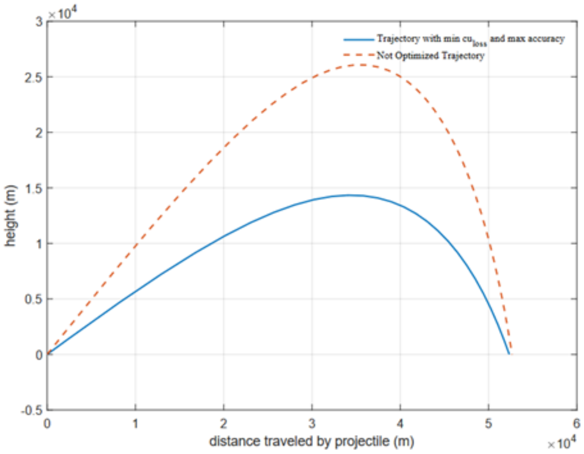

Fig. 10. Projectile path for optimized path and not optimized path.

5. CONCLUSION

An efficient approach is presented in this paper for modeling railguns and projectile paths are very useful for sensitivity and optimization problems be-cause the model's processing speed in simulation software is very high. In the next step, the circuit model of the railgun and the projectile path is simulated inMATLAB. Also, the parameters affecting the target location have been studied, and the cost function has been introduced based on it. Then, optimized parameters are obtained by the genetic algorithm, and by using optimized parameters, losses and costs are drastically reduced. Finally, based on using genetic algorithms and cost function, approximately the losses 109 watts are reduced.

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