ARMATURE SHAPE OPTIMIZATION OF AN ELECTROMAGNETIC LAUNCHER USING GENETIC ALGORITHM

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Abstract

Barrel side and pulsed power supply module are two crucial parts of an electromagnetic launcher (EML), which affects the efficiency. One of the most important features in the barrel side is the shape of the armature. In this study, the shape of the armature is optimized by using independent variables to define the exact geometry of the armature. The main goal is to maximize the muzzle kinetic energy of the projectile. Armature geometry is divided into pieces which are used in the optimization algorithm as independent variables. Finite element method (FEM) is used to calculate the fitness function of the genetic algorithm (GA).

I. INTRODUCTION

EML, also called railgun, is an electromagnetic device that converts the electromagnetic energy into the mechanical energy. It consists of two parallel rails, an armature which are conducting and one projectile which is an insulator. Large amount of pulse current is generated by pulse power supply to excite EML. The current flows through the rails and armature. Current pulse generators connect each other in parallel to keep the current in its peak value longer. The current creates a magnetic field which causes an electromagnetic force. Repulsive electromagnetic force on armature accelerates the armature and projectile.

There exist a number of parameters on the barrel side and pulsed power supply module that affect the EML efficiency. In this paper, the effect of the shape of conducting armature on the muzzle kinetic energy of the projectile is investigated. Ellis et al. [1] observed the effect of square, rectangular, and round bore geometries on the key railgun system parameters without any change of C-shaped armature geometry. Hu et al. [2] also developed an optimization algorithm for both pulsed power system and barrel side parameters to get maximum muzzle velocity with projectile masses ranging from 20 to 50 g by using a mathematical modeling approach. This study does not focus on the shape of conducting armature. In addition, Pitman et al. [3] performed an iterative approach to the EML muzzle velocity optimization problem without using FEM.

In the literature, only a few number of studies focused on the shape of conducting armature, as the calculation of electromagnetic force on the armature for different geometries using analytical methods is a complex approach. For this purpose, using FEM is a plausible idea, however, using FEM as a fitness function of an optimization algorithm increases the computational time depending on the number of mesh elements of FEM model, population size and the number of iterations of the GA.

In this study, MATLAB is used for GA implementation, while COMSOL Multiphysics is used for electromagnetic finite element calculation.

II. OPTIMIZATION METHODOLOGY

The aim of the optimization study is to maximize the projectile muzzle kinetic energy. To excite the railgun, five identical current pulse generation modules are fired at different instants. Current excitation is implemented in FEM with 500k-Amperes peak current. Time dependent study of COMSOL Multiphysics solver is used to calculate the armature repulsive force for each time step of the solver until the current reaches its first peak value. From the energy stored in an inductor, Eq. (1) states that the armature repulsive force is proportional to the square of excitation current where F is the repulsive force on the armature, L' is the derivative of EML inductance with respect to the armature position, and I is the excitation current.

$$F = \frac{1}{2} L' I^2 \tag{1}$$

Because of the proportionality between the square of the current and the armature force, solving the FEM model until the current reaches its peak value is enough to

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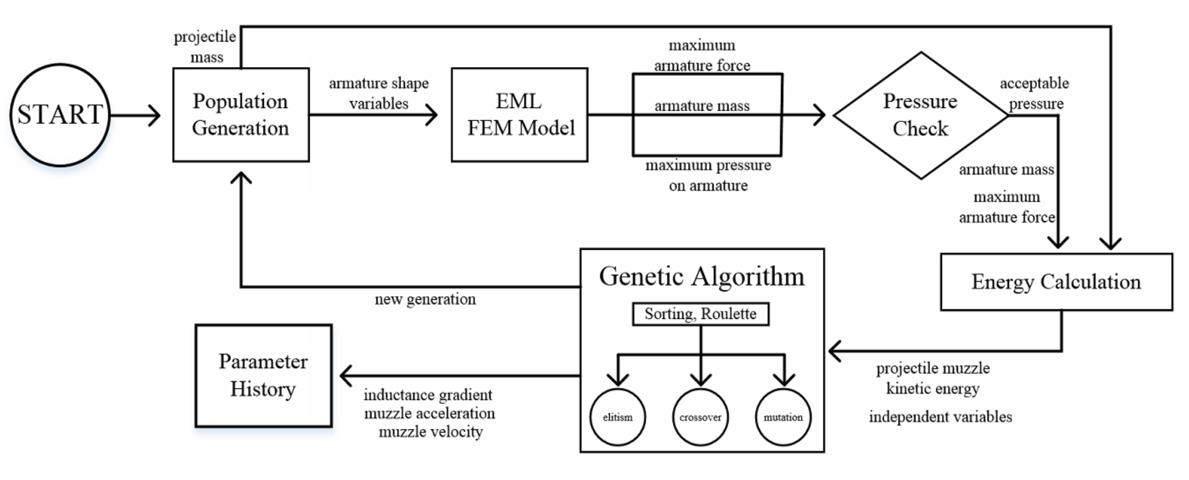


Figure 1. Flow chart of armature shape optimization.

conclude full repulsive armature force waveform. Hence, scaling the waveform with respect to armature force over the square of the current gives full armature force waveform. This approach significantly reduces the computational cost. As the model is solved using time dependent solver instead of stationary solver, it is possible to take the skin and proximity effect into account.

Fig. 1 presents the flow chart of the full optimization process. Optimization algorithm starts with population generation, which includes 7 independent variables, 6 from armature geometry and 1 from the projectile mass. As the projectile mass does not affect the repulsive electromagnetic force, it is not defined in FEM model. Independent variables of the armature geometry used in the study are given in Fig. 2. During the population generation, geometric limits of independent variables are defined as constraints.

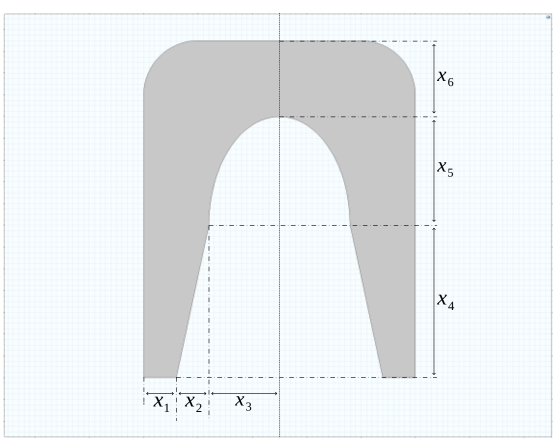


Figure 2. Armature shape optimization parameters.

Since, the temperature of the armature increases during the firing process, tensile strength of the aluminum alloy material used in the armature decreases. Hence, the maximum acceptable pressure on the armature is limited to 100MPa, considering the worst case. After the calculation of total armature force waveform and armature mass by using FEM, optimization algorithm checks whether the pressure is acceptable or not. If pressure constraint and geometric limits are satisfied, full armature force waveform is calculated as previously described. Repulsive armature force accelerates armature and projectile together. Therefore, in order to calculate the acceleration waveform, Eq. (2) is used where m_a is the armature mass, m_p is the projectile mass and a is the acceleration.

$$a = \frac{F}{m_a + m_p} \tag{2}$$

As previously stated, the fitness function of the optimization algorithm is the muzzle kinetic energy of projectile. By means of projectile mass and acceleration waveform, fitness function can be calculated as in Eq. (3) where E_p is the projectile muzzle kinetic energy.

$$E_p = \frac{1}{2} m_p \left(\int a dt\right)^2 \tag{3}$$

Genetic algorithm module takes fitness function and randomly generated geometry as input and continues with the next generation [4]. In order to find the optimum geometry on hyper-space, unique sort and select methods are implemented. Once a population is sorted according to their fitness function, elitism, crossover and mutation filters are applied. Elitism filter simply selects top n-tier individuals and drops others. Crossover filter takes two individuals from population pool and interchange their independent variables to create new ones. Rather than using totally random selection in crossover filter, roulette wheel selection [5] is used. Therefore, population converges faster to the intended point. In order not to get stuck on a local maximum, mutation filter randomly changes the geometry of armature and projectile mass.

III. RESULTS

In the optimization algorithm, population size and number of iteration are selected as 20 and 50, respectively. For these hyper-parameters, the change of independent variables during the optimization process is given in Fig. 4. Note that, while red lines show the change of the fittest individual in each generation, blue dots represent the distribution of the other individuals. Darker blue dot means larger individual density in the population. In the optimization, rail-to-rail distance is kept constant as 25mm. The optimum solution, which gives the maximum projectile muzzle kinetic energy, for x_1, x_2, x_3, x_4, x_5 and x_6 is given in Table 1.

Table 1. Optimum solutions of geometric independent variables.

x_1	x_2	x_3	x_4	x_5	x_6
1.9mm	4.1mm	6.5mm	6.4mm	7.9mm	5.1mm

In Fig. 3, optimum C-shaped armature geometry with the rails is given. Fig. 3 also shows the optimum armature shape and the current density distribution in the rails and armature at the instant when the current reaches its peak value.

As described in [6], C-shaped geometry is favorable for maximum repulsive force, since it increases the magnetic

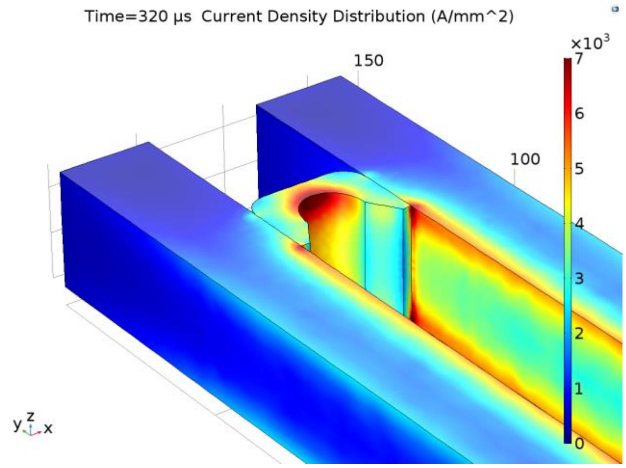


Figure 3. Current distribution in the rails and optimum armature geometry.

flux density behind the armature. Moreover, although shorter armature increases the repulsive force, it also increases the pressure, which damages the limb part of C-shaped armature. Therefore, the height of armature which is equal to the sum of x_4, x_5 and x_6 is limited by pressure constraint which is chosen as 100MPa in the algorithm. In addition to the height, mass is another significant parameter which affects the repulsive force on the armature. If the goal of the optimization was to maximize

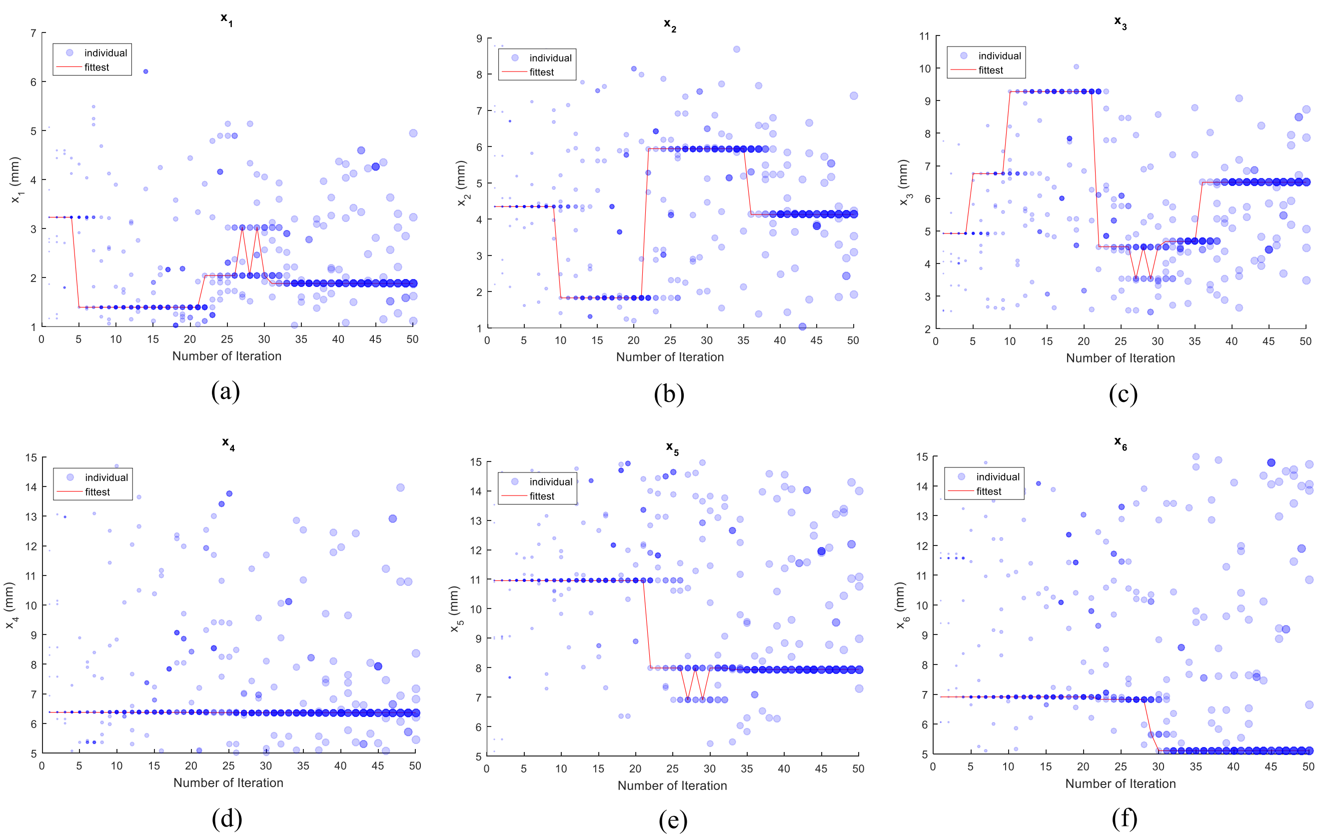


Figure 4. Change of the independent variables during the optimization.

the force, algorithm would try to expand the armature volume. However, in this study the fitness function is kinetic energy of projectile. Although large amount of armature mass increases the repulsive force, it also decreases the acceleration, see Eq. (2). Therefore, x_4 and x_5, which affect the armature mass significantly, do not converge neither to the lower nor to the higher boundaries (see Fig. 4d and 4e). Another geometric parameter which affects the magnetic flux density behind the armature is x_6. Smaller x_6 increases the current density on the rear surface of the armature which causes the larger magnetic flux density behind the armature. However, this situation results in excess temperature rise in this part of armature. Therefore, lower boundary for this independent parameter is required to prevent the excess heating (see Fig. 4f). In addition to the armature shape parameters, the last optimization parameter is the projectile mass. This parameter does not affect the magnetic repulsive force; however, it has an influence on the acceleration and kinetic energy. From Eq. (3), it can be stated that the change in acceleration with projectile mass is more influential on the muzzle kinetic energy of projectile. Hence, in order to increase the fitness function, algorithm tries to decrease it to its lower boundary value, which is 200g in the study. Note that drag force on the projectile and maximum range of the projectile are not taken into account in this study.

Progress of the fitness function value, muzzle velocity, peak acceleration of the projectile and inductance gradient as a function of generation number are given in Fig. 5. Their optimum values are given in Table 2.

Table 2. Results of optimization study.

Projectile Kinetic Energy	Muzzle Velocity	Peak Acceleration	Inductance Gradient
42kJ	900m/s	43,500m/s^2	0.36 μH/m

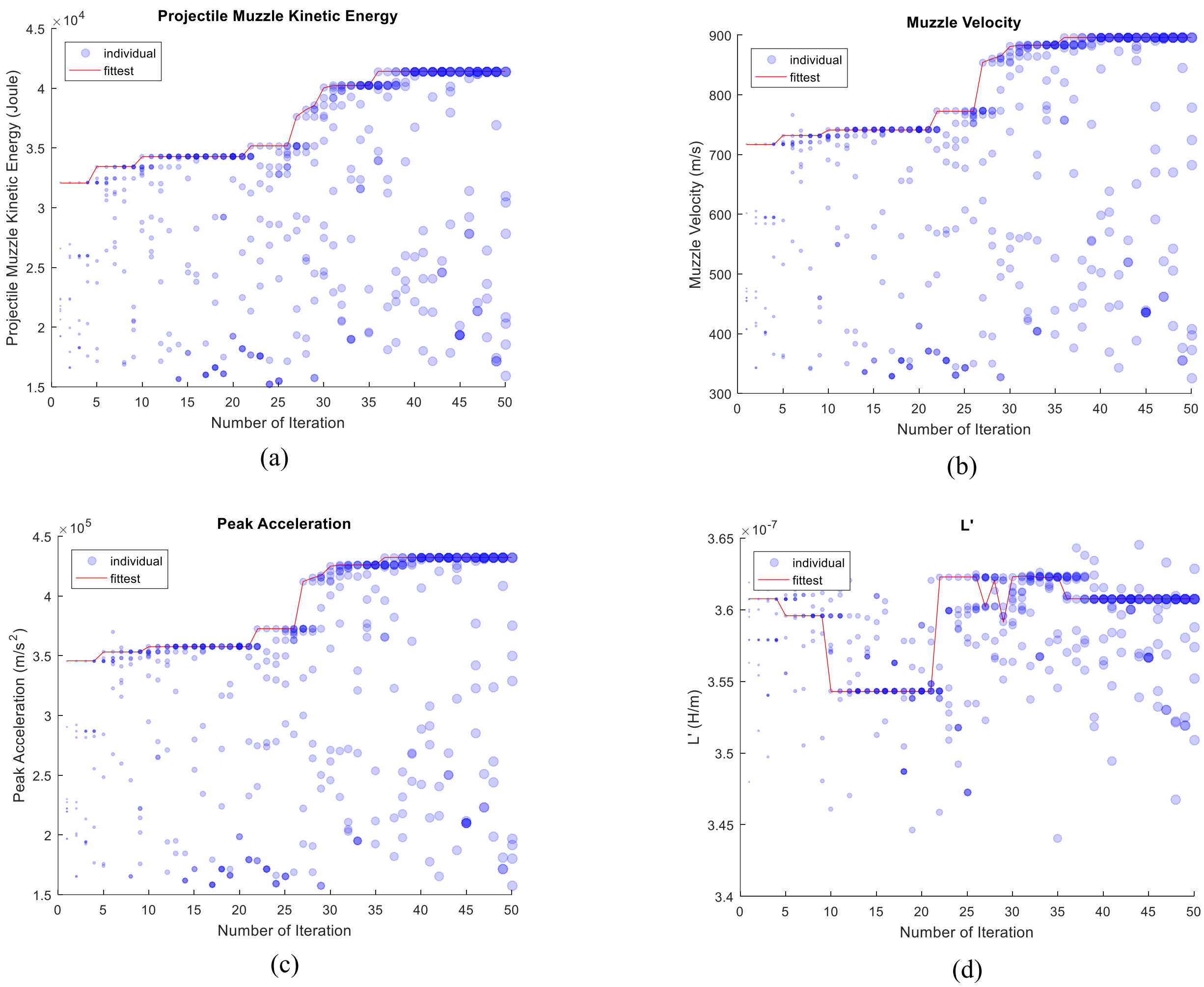
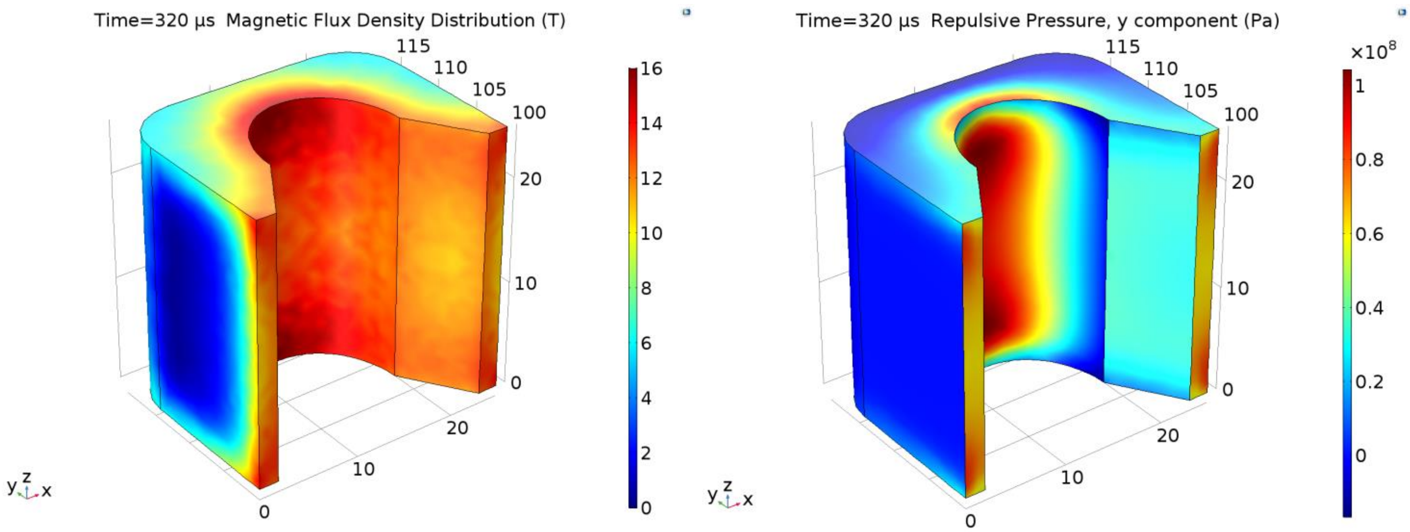


Figure 5. Change of the algorithm outputs during the optimization.



(a) (b)

Figure 6. Optimum armature geometry; (a) magnetic flux density, (b) repulsive pressure in y-direction.

Note that armature and projectile have the same velocities and acceleration during their motion between the rails. To have the maximum projectile muzzle kinetic energy, maximization of velocity and acceleration is essential [7]. However, the inductance gradient is related with the repulsive electromagnetic force on the armature [8], see Eq. (1). Therefore, its value varies during the optimization.

EML is an energy conversion system which converts the stored electrical energy to the kinetic energy. During the conversion, efficiency is very crucial. The factors which influence the energy conversion efficiency of EML is listed with some experimental results in [9]. Theoretical efficiencies of EMLs depend on muzzle velocity and launcher constant which is related with EML geometry [10]. Therefore, maximization of muzzle kinetic energy of projectile with the optimization of armature shape is one of the methods that increases the efficiency. In this study, with calculated maximum muzzle kinetic energy of the projectile, efficiency of EML is approximately 5% by considering the total energy of pulse power supply modules. Efficiency is 10% with both armature and projectile kinetic energy.

In addition, magnetic flux density and repulsive pressure distribution on the optimized armature geometry are available at the instant when the current reaches its peak value in Fig. 6. For the resulting armature shape maximum magnetic flux density is 16T and maximum repulsive pressure in y-direction is 104MPa. C-shaped armature geometry enhances these parameters.

IV. SUMMARY

The shape of the armature is one of the most crucial parameters that affects the muzzle kinetic energy of projectile of an EML. The aim of this study is to develop an algorithm which finds the best armature shape for the maximum efficiency. Since calculating armature repulsive force for different shape analytically is a complex problem, finite element is used for this analysis. EML system is a multiphysics problem. Therefore, in addition to the electromagnetic concepts like skin and proximity effects, mechanical issues have taken into account like damaging pressure on the armature limb in x-direction. It is concluded that although using shorter armature increases the repulsive electromagnetic force, it also increases the pressure beyond a value that damages the material. In addition, C-shaped armature geometry increases the magnetic flux density behind the armature. It is also possible to increase the magnetic flux density by decreasing x_6 (see Fig. 4f). However, it causes the temperature to rise in that section of the armature. One interesting outcome of this study is that the maximum armature repulsive electromagnetic force does not mean the maximum projectile muzzle kinetic energy (see Fig. 5d). Furthermore, armature mass is an essential parameter for maximum energy optimization. In order to reduce the armature mass, x_3, x_4 and x_5 are the most important parameters. The converged values of these parameters can be seen from Fig. 4c, 4d and 4e.

V. ACKNOWLEDGEMENTS

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