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, Poynor, McGlasson, and Smith [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, Ma, Yang, and Wang [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 g to 50 g by using a mathematical modeling approach. This study does not focus on the shape of conducting armature. In addition, Pitman, Ellis, and Bernardes [3] performed an iterative approach to the EML muzzle velocity optimization problem without using FEM.

In the literature, the number of investigations focused on the shape of conducting armature is few. Since the calculation of electromagnetic force on armature for different armature geometries with analytical methods is a complex approach. For this purpose, using FEM is a plausible idea. However, note that using FEM as a fitness function of an optimization algorithm comes with some handicaps. It 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 FEM calculation. To combine COMSOL Multiphysics FEM model with MATLAB scripting, LiveLink for MATLAB is used.

II. OPTIMIZATION METHODOLOGY

The aim of the optimization study is to maximize the projectile muzzle kinetic energy. Five identical current pulse generation modules are fired at different instants to excite the railgun. Current excitation is implemented in FEM with 0.5 MA 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 during the firing 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.

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

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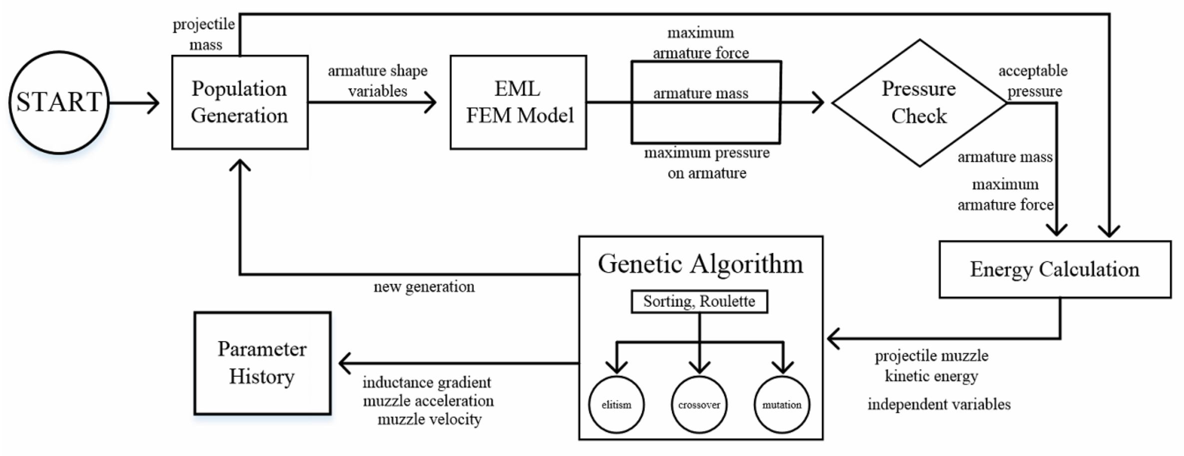


Figure 1. Flow chart of armature shape optimization.

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 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 reduces the computational cost significantly. In addition, it takes the skin effect concept into account because of using time dependent solver rather than the stationary solver.

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

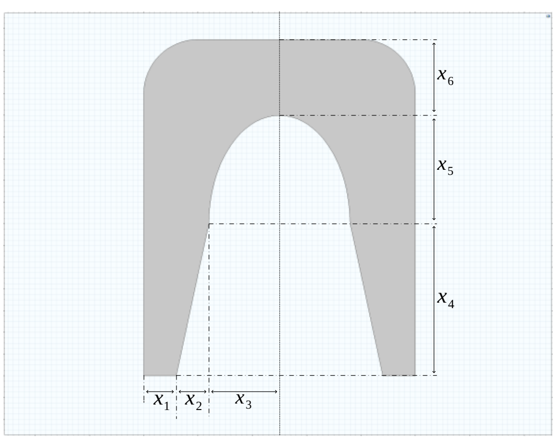


Figure 2. Armature shape optimization parameters.

Since, armature is heated up during the firing process, tensile strength of the aluminum alloy material of armature decreases. Hence, maximum acceptable pressure on the armature should be taken into consideration. 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, for randomly selected armature geometry, full armature force waveform is calculated with the process described before. Repulsive armature force accelerates armature and projectile together. Therefore, in order to calculate the acceleration waveform, Eq. (2) is used.

$$a = \frac{F}{m_{armature} + m_{projectile}} \tag{2}$$

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).

$$E_{projectile} = \frac{1}{2} m_{projectile} \left(\int a dt\right)^2 \tag{3}$$

Genetic algorithm module takes fitness function and randomly generated geometry as input and creates more optimized new generation [4]. In order to find optimized 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 intended point. In order not to get stuck on local maximum, mutation filter changes the geometry of armature and projectile mass randomly.

The discussion of optimization results is available in the next chapter.

III. RESULTS

In the optimization algorithm, population size and number of iteration are selected 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 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 respectively 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 current density distribution in the rails and optimum armature shape 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 flux density behind the armature. Moreover, although smaller armature height increases the repulsive force, it also increases the pressure, which damages the leaf part of C-shaped armature. Therefore, the height of armature which is equal to sum of x_4, x_5 and x_6 is limited by pressure constraint 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 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

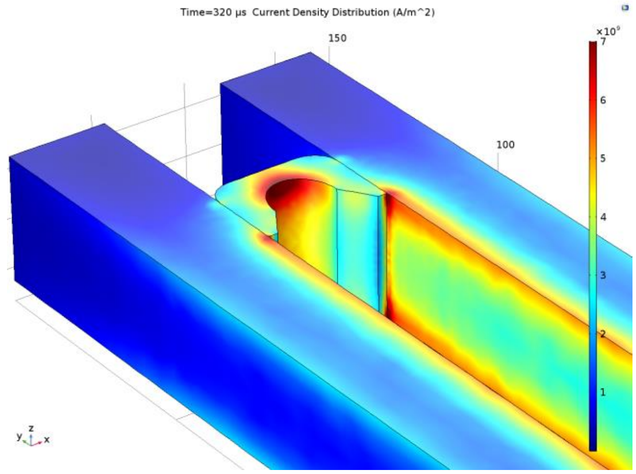


Figure 3. Current distribution in the rails and optimum armature geometry

acceleration, see Eq. (2). Therefore, x_4 and x_5, which affect the armature mass significantly, do not converge neither lower nor higher boundary. Another geometric parameter which affects the magnetic flux density behind the armature is the length of x_6. Smaller x_6 leads to increase 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 extra heating in this part of armature. Therefore, lower boundary for this independent parameter is required to prevent the extra heating. In addition to the armature shape parameters, 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

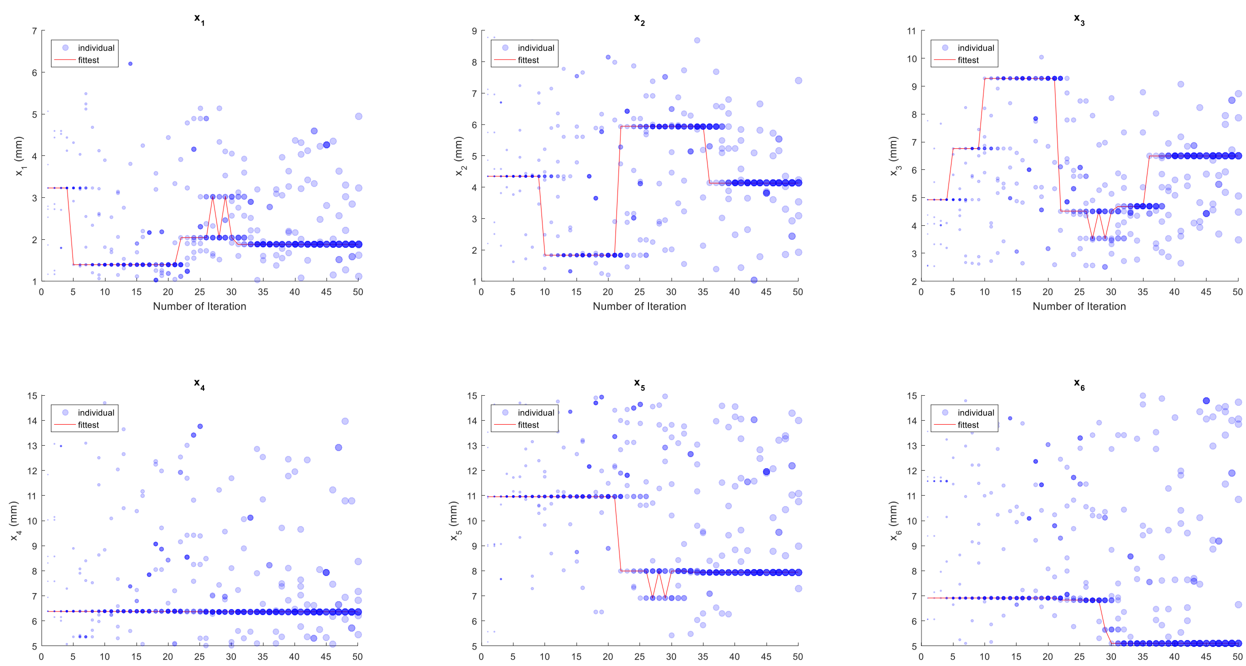


Figure 4. Change of the independent variables during the optimization

be stated that the change of acceleration with mass of projectile 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 200 g in the study. Note that drag force on the projectile and maximum range of the projectile are not taken into account in this study**.**

Change of the fitness function, muzzle velocity, peak acceleration of the projectile and inductance gradient during the optimization is given in Fig. 5. Their optimum values are respectively 42kJ, 900m/s (2.6 Mach), 43500 m/s^2 and 0.36 H/m. Note that armature and projectile have the same velocity 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, it takes different values 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 efficiency of EMLs depends on muzzle velocity and launcher constant which is related with EML geometry [10]. Development of theoretical efficiency is a critical concept in EML technology. Therefore, maximization of muzzle kinetic energy of projectile with the optimization of armature shape is one of the ways 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.

Moreover, 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.

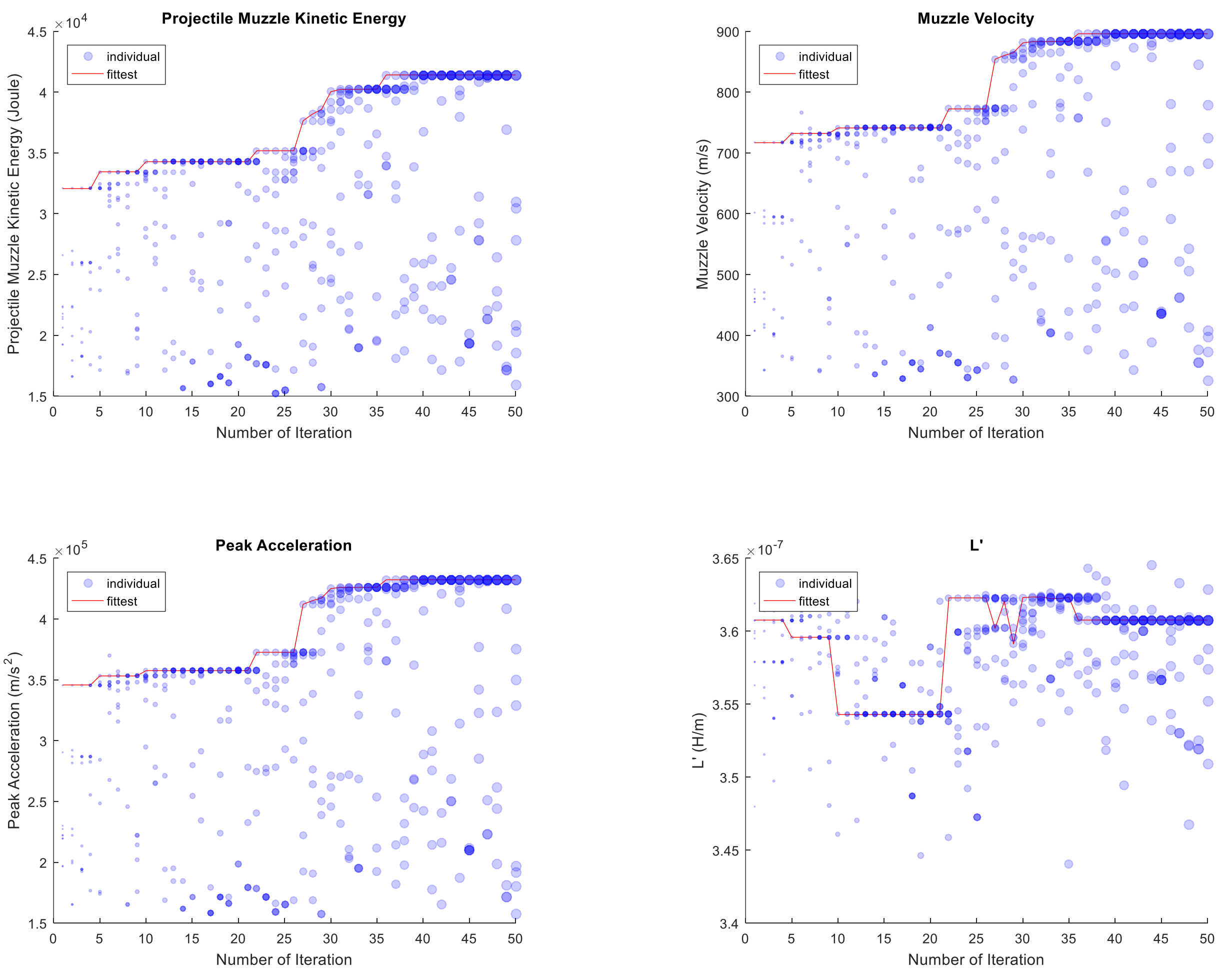
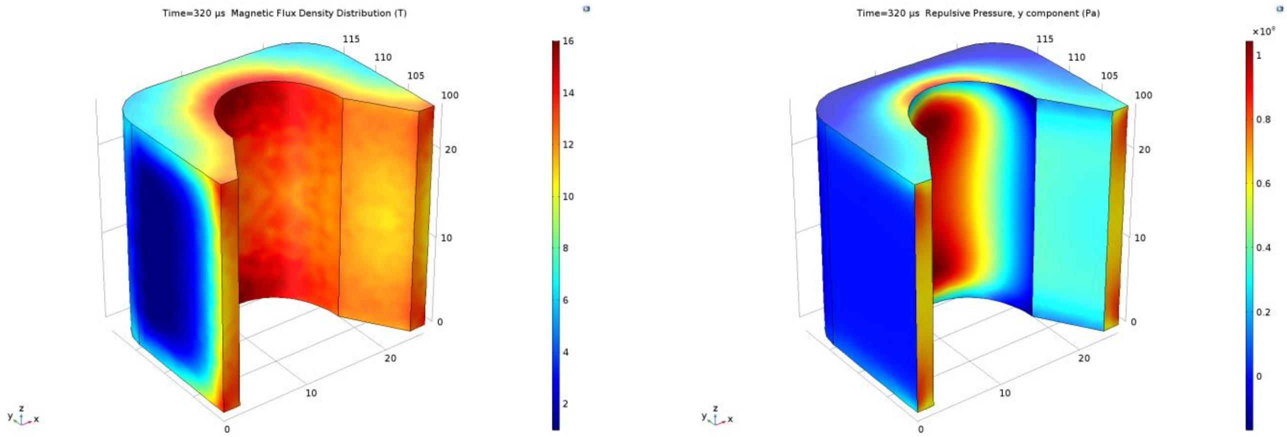


Figure 5. Change of the algorithm outputs during the optimization



(b)

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

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 the investigation is to develop an algorithm which finds the best armature shape to increase the efficiency. Since calculating armature repulsive force for different shape analytically is a complex problem, using FEM for this purpose is a good idea. EML system is a multiphysics problem. Therefore, in addition to the electromagnetic concepts like skin and proximity effects, mechanical issues have to be taken into account like damaging pressure on the armature leaf in x-direction. In this study, it is considered as a constraint for the optimization algorithm. However, drag force on the projectile during the motion is not observed in the paper. Also, analysis is implemented by using stationary solver. Hence the velocity skin effect concept is not considered which changes the current distribution in the armature. These concepts are future works of the study which will make the investigation more realistic.

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