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Optimization Design of Multi-Parameters in Rail Launcher System

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Abstract: Today the energy storage systems are still encumbering, therefore it is useful to think about the optimization of a railgun system in order to achieve the best performance with the lowest energy input. In this paper, an optimal design method considering 5 parameters is proposed to improve the energy conversion efficiency of a simple railgun. In order to avoid costly trials, the field-circuit method is employed to analyze the operations of different structural railguns with different parameters respectively. And the orthogonal test approach is used to guide the simulation for choosing the better parameter combinations, as well reduce the calculation cost. The research shows that the proposed method gives a better result in the energy efficiency of the system. To improve the energy conversion efficiency of electromagnetic rail launchers, the selection of more parameters must be considered in the design stage, such as the width, height and length of rail, the distance between rail pair, and pulse forming inductance. However, the relationship between these parameters and energy conversion efficiency cannot be directly described by one mathematical expression. So optimization methods must be applied to conduct design. In this paper, a rail launcher with five parameters was optimized by using orthogonal test method. According to the arrangement of orthogonal table, the better parameters' combination can be obtained through less calculation. Under the condition of different parameters' value, field and circuit simulation analysis were made. The results show that the energy conversion efficiency of the system is increased by 71.9 % after parameters optimization. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Electromagnetic launching, Energy conversion, Field and circuit analysis, Optimization method.

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1. Introduction

There are typically three different kinds of railguns according to the rail structure: the simple railgun, the augmented railgun, and the muzzle-fed railgun [1]. The most often used simple railgun consists of two parallel rails and a sliding armature, as shown in Fig. 1. Today the energy storage systems which feed the railguns are still large, and it is important to consider the minimization of the stored energy. This can be done by determining the minimal energy necessary to achieve a given performance. The PFN is related to the choice of the energy source. However, it is not easy to optimize the electric circuit because the components used at high currents have still large electrical resistances and if diodes are used as crowbar switch, the resistance of circuit cannot be lowered under a certain value given by the manufacturer [2]. In addition, one can also optimize the efficiency of the railgun. The optimization design, leading to an increase of the railgun overall efficiency, is a very complex process because there are many significant factors to consider, such as structural geometry parameters affecting inductance gradient, mass and initial position of armature, charging voltage, capacitor of power supply, pulse shaping inductance, etc. [3-6].

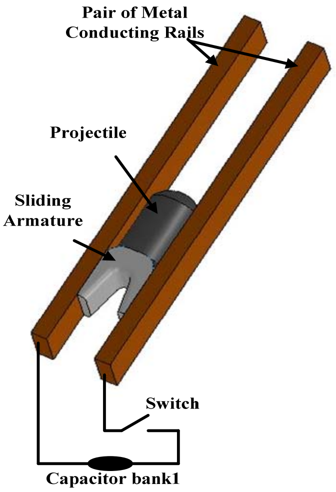


Fig. 1. Schematic diagram of a simple railgun.

In 3-D finite element analysis, we consider the influence of the size, shape and material of rails on inductance gradient. Moreover, analysis of circuit simulation can reveal that the influence of circuit parameters on railgun efficiency. However, it will take a great deal of time to analyze the optimization design by considering so many factors. This can be solved by a control parameter optimization algorithm based on the orthogonal test approach [7-9].

This paper deals with five parameters encountered in the design of a simple railgun with field-circuit method and orthogonal test approach. Firstly, according to the number of factors and value of each factor, we select the appropriate orthogonal array to arrange the simulations. Secondly, we use mathematical statistical approach to process data. Finally, we can find the main factor which has a significant influence on railgun efficiency, and determine the value of the main factor. By orthogonal design method, we can determine a scientific experiment scheme for field-circuit simulation. Accurate analysis and effective optimization design are essential to avoid costly trials. Results indicate that the energy conversion efficiency of the system is increased by 71.9 % after parameters optimization.

2. Orthogonal Test Approach

The orthogonal test approach, based on the combinatorial theory, has been developed to reduce the number of tests. With this approach, only a part of the tests needs to be conducted instead of the complete set of tests [7-9]. The performance of railgun can be evaluated by the energy conversion efficiency, which depends on many factors, the control parameters. Each of such factors can be considered as a discrete variable with numerous "levels". The railgun efficiency varies with the change of the level of each factor. The best combination is expected to be achieved by tuning these parameters.

There are two key elements in the orthogonal test approach. One is to design an orthogonal table, i.e. to select the tests needed to be done among the complete set. The other is to analyze the test results, i.e. to determine best level of each factor.

2.1. Design of the Orthogonal Table

According to the number of factors and levels, we will construct an orthogonal table $L_t^u\ (t^q)$ [8]. Here, t is the number of the levels. It must be a prime number or the power of the prime number. And u is the number of the basic columns. It can be any positive integer. Then t^u is the number of tests to be conducted. The maximum number of columns in the tables is q, given by

$$q = \frac{t^u - 1}{t - 1}, \tag{1}$$

where q corresponds to the number of factors.

Among the q columns, the basic columns are respectively are No. 1, 2, $[(t^2-1)/(t-1)]+1$, …, $[(t^{u-1}-1)/(t-1)]+1$. These columns are named with the letters: a, b, c, …. According to the certain rules [7], the levels of the basic and the rest columns can be arranged. In some cases, the influence of one factor on the system is related to another factor. The best match of these two parameters should be considered when there exists interaction between two factors.

2.2. Analysis of Test Results

The purpose of the control parameter optimization by orthogonal test approach is to search for better parameters' combination in the neighboring space of the present ones. For the analysis of results, through range and variance analysis, there are three main steps. Firstly, the average value of each level in each column and the range of each factor are calculated by

$$k_{ij} = \frac{\sum_{i=1}^{n} J_i}{n}, \tag{2}$$

$$R_j = k_{ij\max} - k_{ij\min}, \tag{3}$$

where j is the column number, i is the level number in j-th column, n is the number of repeat of i-th level, and J_i is the test result corresponding to i-th level. Secondly, the primary and secondary order of factors can be obtained by comparing the range of all factors. Finally, according to the value of k_{ij}, the better combinations of levels are selected. However, if the interaction between two factors (e.g. A and B) has the more significant influence on system than factor B, the level of factor B must be determined by the combination of factor A and factor B [7].

3. Field-Circuit Method

To calculate the energy conversion efficiency, a 3-D eddy current electromagnetic field finite-element numerical analysis model is firstly established. The inductance gradient (L') is calculated by using this model. Then the value of L' is substituted into the circuit control equations. The energy conversion efficiency can be obtained by circuit simulation.

3.1. 3-D Finite-Element Analysis

To calculate the parameter, the excitation current is applied to the rail pair. According to the principle of circuits, the value of inductance (L) can be obtained [10].

The voltage of the loop is given by

$$\dot{U} = R\dot{I} + j\omega L\dot{I}, \tag{4}$$

The real part and imaginary part of the voltage is given by

$$U_r + jU_i = RI_r + jRI_i + j\omega LI_r - \omega LI_i, \tag{5}$$

$$U_r = RI_r - \omega LI_i, \tag{6}$$

$$U_i = RI_i + \omega LI_r, \tag{7}$$

According to (6) and (7), we can get the inductance.

$$L = \frac{U_r I_i - U_i I_r}{2\pi f(I_r^2 + I_i^2)}, \tag{8}$$

The inductance gradient (L') can be calculated using interpolation by (9).

$$L'(x) = \frac{L(x+\Delta x) - L(x-\Delta x)}{2\Delta x}, \tag{9}$$

3.2. Circuit Simulation

The control equations are given in (10)-(13). The equations can be solved by fourth-order Runge Kutta method [10].

$$\frac{du_c(t)}{dt} = -\frac{1}{C}i(t), \tag{10}$$

$$\frac{dv}{dt} = \frac{F-f}{m} = \frac{\frac{1}{2}L'i(t)^2 - f}{m}, \tag{11}$$

$$\frac{di(t)}{dt} = \frac{u_c(t) - (R_0 + R'x)i(t) - L'v(t)}{L_0 + L'x}, \tag{12}$$

$$\frac{dx}{dt} = v, \tag{13}$$

where $u_c(t)$ is the capacitor bank voltage, L_0 is the pulse forming inductance, R' is the resistance gradient of rail, L' is the inductance gradient, x is the position of armature, and v is the velocity of armature.

4. Conventional Railgun Design

We designed a conventional railgun, the parameters of which are shown in Table 1.

Table 1. Parameters of the railgun.

Parameters	Value
Width of rail (mm)	10
Height of rail (mm)	30
Length of rail (m)	2.2
Distance between rail pair (mm)	30
Mass of armature and projectile (g)	70
Pulse forming inductance (μH)	3
Capacitor bank initial storage energy (kJ)	1000

4.1. L' Calculation

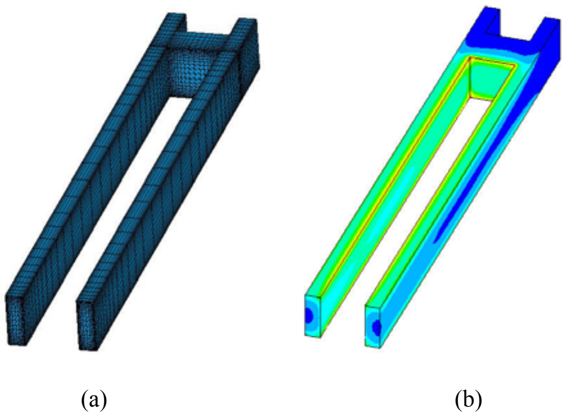
The geometrical parameters and material properties demonstrated in Fig. 1 and Table 1 are used to calculate L', and the sinusoidal ac frequency is set to 500 Hz in the 3-D harmonic magnetic analysis [10, 11]. The finite-element meshes of rails and armature are shown in Fig. 2 (a).

The current density distributions, shown in Fig. 2(b), represent that a skin effect exists on the inside of rails. The inductance gradient (L') is 0.56 μH/m.

4.2. Energy Conversion Efficiency Calculation

In addition to circuit parameters in Table 1, other parameters used in simulation are: $u_c(0)$= 5 kV, C= 80 mF, R_0 = 2 mΩ, $f = \frac{1}{2}\alpha I^2$ [12].

The results of the launch process calculation are respectively shown in Fig. 3. The velocity of armature is 1012.2 m/s, so the energy conversion efficiency is 3.59 %.



(a) (b)

Fig. 2. Finite-element calculation. (a) Meshes of model.

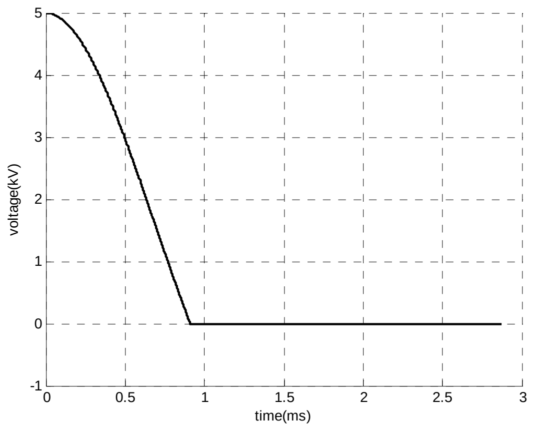


Fig. 3 (a). Calculation results of circuit simulation: Voltage waveform.

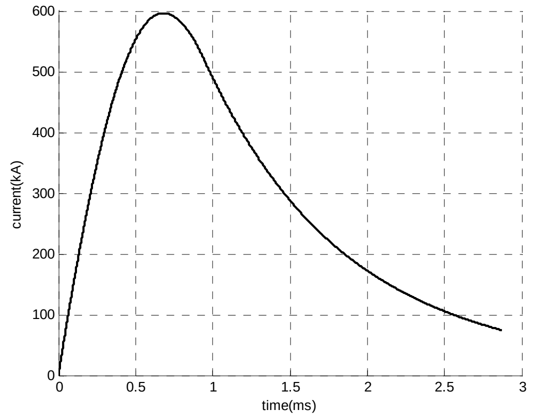


Fig. 3 (b). Calculation results of circuit simulation: Current waveform.

5. Parameter Optimization

Under the condition that the initial storage energy of capacitor bank is kept constant, the energy conversion efficiency is regarded as target function, while the five parameters are optimized by orthogonal test approach. The main steps are:

1) Selection of factors. To simplify the analysis, only the important parameters that have significant influence on the performance should be considered. Selection of the levels. Most parameters are considered as discrete variables by dividing them into levels. The interval between two consecutive levels cannot be too large to miss the optimal level.

2) Creation of an orthogonal table.

3) Performance of tests.

4) Synthesis of the test results to determine the best parameters.

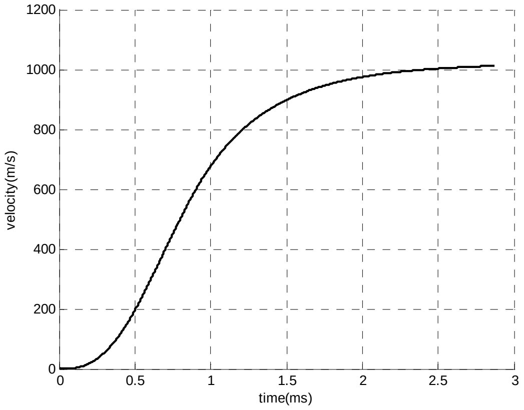


Fig. 3. Calculation results of circuit simulation: Velocity waveform.

5.1. Selection of Levels

The majority of railgun architecture changes to improve efficiency have involved modifying the rail geometry to increase the L' of the launcher. The L' of a simple railgun can be changed by adjusting the shape and distance between the rails [3]. Moreover, from the (12), the pulse forming inductance has the impact on the current waveform. Therefore, we select five parameters as variables, including the width, height, length and distance of rail pair, and the value of pulse forming inductance.

5.2. Selection of Factors

To search for better parameters in the neighboring space of the present ones, we select three levels for each factor. In addition, the present level of each parameter should be in the list selected because the present parameters of the system are the base of the optimization.

5.3. Orthogonal Table

According to the number of factors and levels, we determine the $t = 3$, $u = 3$, so $q = 13$ by using (1), so a L_{27} (3^{13}) orthogonal table as demonstrated in Table 2 is employed. Twenty seven simulations must be done. However, if we conducted the complete tests, it needs $3^5 = 243$ simulations. The interaction between the parameters is considered. Nevertheless, because several interactions exist in the same column, these columns cannot be arranged.

Table 2. Orthogonal Table

Column	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
Factors **Test**	**Width(a)**	**Height(b)**	**a×b**	**Length(c)**	**Distance(d)**	**a×d**	**L_0(e)**	**b×d**	**Results**
1	5	20	1	2.0	30	1	2.5	1	5.28 %
2	5	20	1	2.0	35	2	3	2	5.41 %
3	5	20	1	2.0	40	3	3.5	3	5.68 %
4	5	30	2	2.2	30	1	2.5	2	3.87 %
5	5	30	2	2.2	35	2	3	3	4.20 %
6	5	30	2	2.2	40	3	3.5	1	4.54 %
7	5	40	3	2.4	30	1	2.5	3	2.91 %
8	5	40	3	2.4	35	2	3	1	3.31 %
9	5	40	3	2.4	40	3	3.5	2	3.72 %
10	10	20	2	2.4	30	2	3.5	1	4.45 %
11	10	20	2	2.4	35	3	2.5	2	5.20 %
12	10	20	2	2.4	40	1	3	3	5.52 %
13	10	30	3	2.0	30	2	3.5	2	3.44 %
14	10	30	3	2.0	35	3	2.5	3	3.91 %
15	10	30	3	2.0	40	1	3	1	4.21 %
16	10	40	1	2.2	30	2	3.5	3	2.53 %
17	10	40	1	2.2	35	3	2.5	1	3.09 %
18	10	40	1	2.2	40	1	3	2	3.60 %
19	15	20	3	2.2	30	3	3	1	4.11 %
20	15	20	3	2.2	35	1	3.5	2	4.44 %
21	15	20	3	2.2	40	2	2.5	3	5.11 %
22	15	30	1	2.4	30	3	3	2	3.27 %
23	15	30	1	2.4	35	1	3.5	3	3.45 %
24	15	30	1	2.4	40	2	2.5	1	4.03 %
25	15	40	2	2.0	30	3	3	3	2.44 %
26	15	40	2	2.0	35	1	3.5	1	2.75 %
27	15	40	2	2.0	40	2	2.5	2	3.42 %
k_1	4.32	5.02	4.04	4.06	3.59	4.00	4.09	3.97	
k_2	3.99	3.88	4.04	3.94	3.97	3.99	4.01	4.04	
k_3	3.67	3.09	3.91	3.98	4.43	3.99	3.89	3.97	
R	0.65	1.93	0.13	0.12	0.84	0.01	0.20	0.07	

5.4. Analysis of Results

In the 27 simulations, the maximal energy conversion efficiency is 5.68 %. Using (2) and (3), the average value of each level in each column and the range of each factor are calculated, as shown in Table 2. By comparing the range of each factor, it is known that the significant order of the five factors and interactions is height > distance > width > L_0 > interaction (width, height) > length > interaction (height, distance) > interaction (width, distance). So, the influence of interactions is less than that of each factor. Moreover, according to the average value of each level, the effect curve of all factors is shown in Fig. 4. It shows that the influence of three levels for factor *c* is approximate. Therefore, we can respectively calculate the results under the condition that the factor c is 2.0 or 2.4. Then, when the factor c is 2.0, the energy conversion efficiency is 6.08 %. Furthermore, when the factor c is 2.4, the energy conversion efficiency is 6.17 %. So, the better combination is as follows: $a = 5$ mm, $b = 20$ mm, $c = 2.4$ m, $d = 40$ mm, $e = 2.5$ μH.

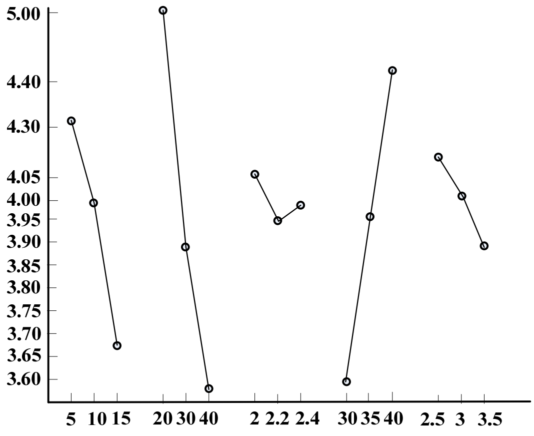


Fig. 4. Effect curve of all factors.

After circuit simulation, the velocity of armature is 1327.8 m/s and the energy conversion efficiency is 6.17 %. Finally, from the optimization, the energy conversion efficiency of the system is increased by 71.9 % after parameters optimization.

6. Conclusion

To research the performance of the railgun, the field-circuit method is applied to calculate the inductance gradient (*L'*) and the energy conversion efficiency. Then, the system of a simple railgun is optimized with orthogonal test approach. The energy conversion efficiency of the system is regarded as the target function, while the width, height, length and distance of rail pair and the value of pulse forming inductance are regarded as variables. For each parameter, three values are selected in the neighboring space of the present ones. Only by 27 simulations, the best parameters' condition is obtained. Results of research indicate that the height of rails is the most significant to the target function and the length of rails has little influence on the target function. The orthogonal test approach is very effective to parameters optimization for railguns.

Acknowledgements

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