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Optimization of Three-stage Electromagnetic Coil Launcher

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Abstract: For the design of three-stage electromagnetic coilgun, many parameters and their relations must be considered at the same time. However, there is no complete mathematical model to describe the relationship between these parameters and energy conversion efficiency of the coil launcher system. In this paper, using orthogonal test approach we consider the influence of 11 parameters to improve the energy conversion efficiency of a three-stage coilgun. Moreover, for the 11 parameters, another three neighboring values of the actual value are considered. According to the different 64 simulations arranged by orthogonal test approach, the 64 groups of muzzle velocity calculated by circuit equations can be analyzed to obtain a better parameters' combination. For the solution of circuit simulations, an improved current filament method is proposed. To validate the optimal design, we manufacture the prototype and the improved one. The experimental results indicate that the optimal design method is effective. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Optimal design, Three-stage coilgun, Energy conversion efficiency, Orthogonal test approach, Improved current filament method.

1. Introduction

The design of multi-stage synchronous induction coilgun (SICG) is a competitive and multi-constrained task that determines the energy conversion efficiency. In the electromagnetic system, the drive coils must be energized separately by the external source, which is controlled by switches, and the currents must be impressed on the armature by external circuit, as shown in Fig. 1. The turning on and off time of switches must be governed by the position of the armature. Moreover, the center-to-bottom space between the drive coils and armature, and the structural parameters of the drive coils and the armature are regarded as variables [1]. The energy conversion efficiency of the system is regarded as an objective function, while optimal design of SICG is a process that involves skills of many parameters' combination.

However, because the relations between these parameters and energy conversion efficiency cannot be described by a general mathematical model, the optimization must be achieved by a large number of repeated computations under the condition of many different parameters' combinations. Therefore, it is difficult to achieve a global optimization to find some better combinations [2]. On the one hand, most of research focus has been on the single-factor influence. For examples, the trigger discharge position of the armature was studied in [3] and [4]. The optimization of drive coils was analyzed in [5]. The structure of armature was designed in [6]. On the other hand, there are only few papers to deal with the multi-factor optimization problem for coilgun [1, 7-9]. For the ant colony algorithm [1] and the genetic algorithm [7-9], the initialization of parameters will directly affect the time of iterative analysis. And it is easy to encounter local optimum by both algorithms. However, using the orthogonal test approach, each test arranged has a strong representation and it can comprehensively reflect the situation in the range of selection. Although the result is not necessarily the best combination in complete tests, it often is a very good condition [10].

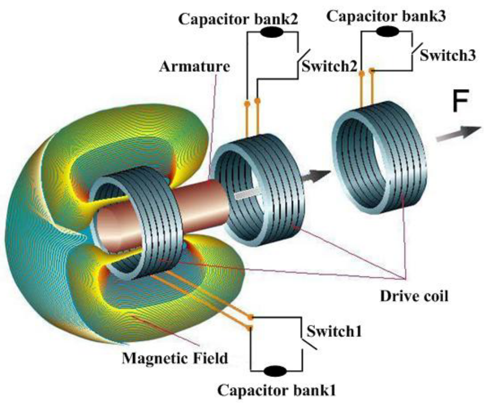


Fig. 1. Structure of a three-stage coilgun.

This paper optimizes eleven parameters in the design of a three-stage coilgun with orthogonal test approach. The improved current filament method (CFM) is employed in the coilgun's circuit simulation [11]. According to the orthogonal test approach, circuit simulations under the different conditions of parameters' combination are arranged to calculate the corresponding muzzle velocity of armature, and through variance analysis, the values of all 11 parameters can be determined for improving the energy conversion efficiency. It can find out significant factors and the adjustment direction of each factor. To validate the results of parameters optimization, an experiment is carried out with two different three-stage coilguns. Results indicate that the energy conversion efficiency of the system is increased by 36 % after parameters optimization.

2. Algorithm Description

2.1. Orthogonal Test Approach

In mathematics, the balanced distribution of parameters' combinations in range of selection is called "orthogonal". 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 need to be conducted instead of the complete set of tests [10, 12-13]. The performance of coilgun, such as the energy conversion efficiency, can be evaluated, which depends on many factors, the control parameters. Each of such factors can be considered as a discrete variable with numerous "levels". The coilgun efficiency varies with the change of the level of each factor. The best combination is expected to be achieved by tuning these parameters.

To simplify the analysis, only the important parameters that have significant influence on the performance should be considered. 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. According to the number of factors and levels, we will construct an orthogonal table L_t^u (t^q) [12]. 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, $[(t^2\text{-}1)/(t\text{-}1)]+1$, …, $[(t^{u-1}\text{-}1)/(t\text{-}1)]+1$. These columns are named with the letters: a, b, c, …. According to the certain rules [10], 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.

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, 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 [10].

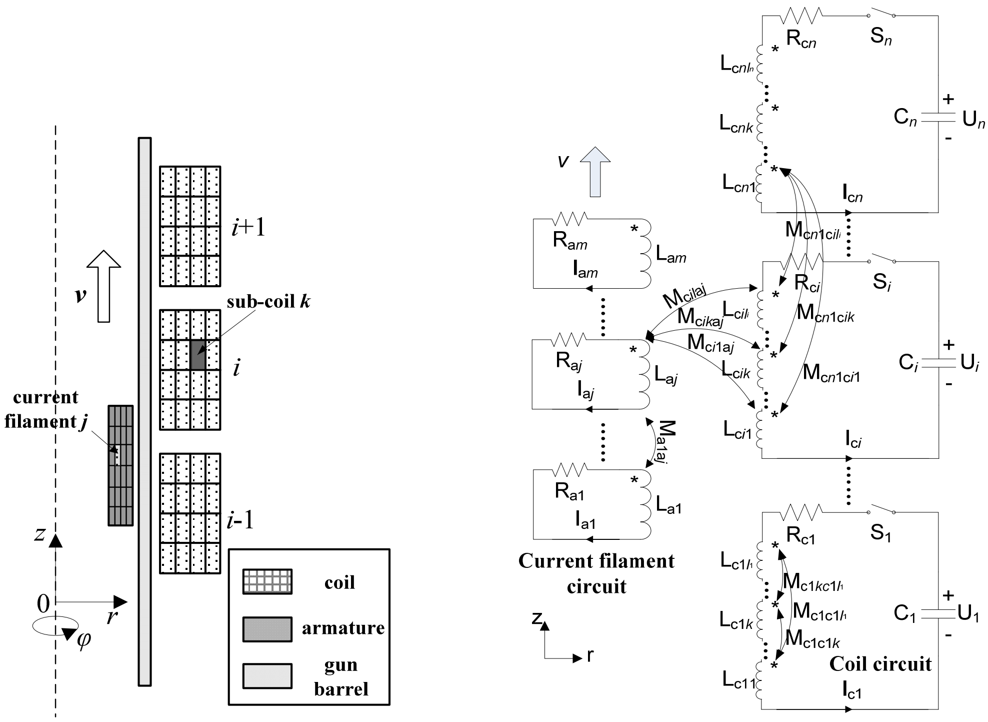
2.2. Improved Current Filament Method

In the improved CFM, the excitation coils are divided into small sub-coils, each excitation coil is equivalent to a set of sub-coils. The mutual inductances between current filaments and excitation coils are replaced by mutual inductances between current filaments and sub-coils. Since the dimension difference between current filaments and sub-coils is much smaller, the calculation precision of mutual inductance is supposed to improve. Schematic diagram of modified CFM is shown in Fig. 2, and the process of circuit simulations can be obtained by [11].

3. Structure of a Prototype

In this paper, we design a three-stage SICG, which consists of drive coils, integrated launch package including an armature, capacitor banks, synchronous control circuits, etc. Three same drive coils are made of circular copper wire, the armature is made of brass tube, and the barrel is made of PVC pipe. In addition, there are totally 24 capacitors and capacitance of each capacitor is 240 μF. In each stage, there are 8 capacitors and the charge voltage of capacitor bank is 1.5 kV.

The mass of armature is 54 g, and its initial velocity is zero. The parameters of the SICG are shown in Fig. 3.



(a) CFM of coil gun (b) equivalent circuit

Fig. 2. Schematic diagram of modified CFM.

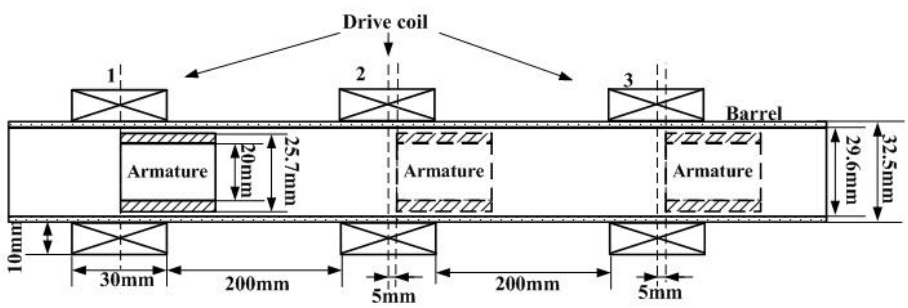


Fig. 3. Schematic diagram that show structural parameters.

Initially, the armature lies in the middle of the first drive coil. When the switch of the first stage turns on and others turn off, the rising current in the first drive coil will induce another reverse current in the armature. When the armature reaches the second drive coil, the switch of the second stage turns on, the armature is accelerated again [1]. So, the trigger discharge position of the armature in each stage drive coil is important to accelerate. The center-to-bottom space between the second, third drive coil and the armature is 5 mm.

4. Parameters Optimization

In the system of SICG, the change of any parameter will affect muzzle velocity of the armature and the efficiency of system [1]. However, under the existing conditions, we cannot increase the efficiency by changing the structure of the armature, the charge voltage and total capacitance of all capacitor banks.

4.1. Selection of Factors

In this paper, because the mass of armature and the charge voltage and total capacitance are constant, the system of SICG is optimized with regard to muzzle velocity of the armature as the objective function and eleven parameters as variables. These parameters include the thickness, length of each drive coil, the number of capacitors and the different trigger discharge position in each stage. The relationship between the muzzle velocity of the armature v and the parameters to be optimized can be expressed as

$$\max v = f(c_1, c_2, p_1, p_2, p_3, l_1, l_2, l_3, t_1, t_2, t_3)\,, \quad (4)$$

where c_1 is the number of capacitors in first stage, c_2 is the number of capacitors in second stage (the number of capacitors in third stage is 24-c_1-c_2.), p_1, p_2, p_3 are respectively the trigger discharge position in each stage, l_1, l_2, l_3 are respectively the length of each drive coil, and t_1, t_2, t_3 are respectively the thickness of each drive coil.

4.2. Selection of Levels

To search for better parameters in the neighboring space of the present ones, we select four levels for each factor, as shown in Table 1. 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.

Table 1. Levels of each factor.

Level \ Factor	c_1	p_1	c_2	p_2	p_3	l_1	l_2	l_3	t_1	t_2	t_3
1	9	-5	6	-15	-15	30	30	30	10	10	10
2	10	0	7	-10	-10	40	40	40	15	15	15
3	11	5	8	0	0	50	50	50	20	20	20
4	12	10	9	5	5	60	60	60	25	25	25

4.3. Orthogonal Table

According to the number of factors and levels, we determine the t = 4, u = 3, so q = 21 by using (1), so a L_{64} (4^{21}) orthogonal table as demonstrated in Table 2 is employed (Due to limited space, only part of arrangement are displayed). Sixty four tests must be done. However, if we conducted the complete tests, it would be 4^{11} = 4,194,304 tests. The interaction between the parameters is considered. Because several interactions exist in the same column, the factors cannot be in these columns.

4.4. Analysis of Results

In the 64 simulations, the maximal velocity is 124.20 m/s. And for the prototype, muzzle velocity of the armature is 108.32 m/s. 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 average value and range, it is known that the first trigger discharge position of the armature in the first stage is the most significant to the objective function. Moreover, the best combination is as follows: c_1 = 12, c_2 = 7, p_1 = 0, p_2 = -10 mm, p_3 = -10 mm, l_1 = 6 mm, l_2 = 7 mm, l_3 = 7 mm, t_1 = 3 mm, t_2 = 3 mm, t_3 = 3 mm. This combination does not exist in the 64 simulations, so we conduct another simulation under the optimized condition. The results are shown in Fig. 4. The muzzle velocity of the armature is 126.62 m/s. So, through the simulations the energy conversion efficiency of the system is increased by 36.6 % after parameter optimization.

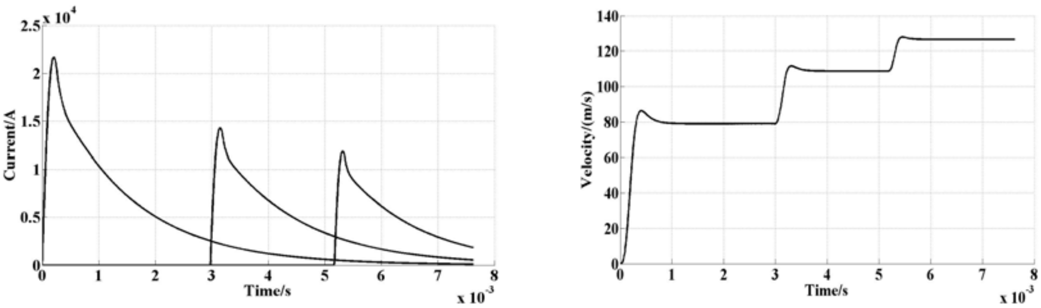
5. Validation of Experiment

To validate the results of the optimization, an experimental system is built and tested as shown in Fig. 5. In the experiment, the muzzle velocity of the armature in prototype and the optimized one is measured respectively.

Table 2. 64 simulations and results.

Column	1	2	9	11	12	13	14	15	16	17	18	
Factor / Test	c_1	p_1	c_2	p_2	p_3	l_1	l_2	l_3	t_1	t_2	t_3	Results
1	9	-5	6	-15	-15	4	4	4	2	2	2	66.52
2	9	-5	7	-10	-10	5	5	5	3	3	3	119.81
3	9	-5	8	-5	-5	6	6	6	4	4	4	108.31
4	9	-5	9	0	0	7	7	7	5	5	5	85.30
5	9	0	6	-10	-10	5	6	6	4	4	5	102.55
6	9	0	7	-15	-15	4	7	7	5	5	4	105.25
7	9	0	8	0	0	7	4	4	2	2	3	109.32
8	9	0	9	-5	-5	6	5	5	3	3	2	124.20
9	9	5	6	-5	-5	6	7	7	5	5	3	109.33
10	9	5	7	0	0	7	6	6	4	4	2	112.17
…	…	…	…	…	…	…	…	…	…	…	…	…
64	12	10	7	0	-10	6	6	5	5	2	3	94.54
k_1	103.15	103.13	104.26	103.93	100.17	102.69	102.69	102.31	104.45	103.12	105.12	
k_2	106.21	109.95	106.52	106.24	106.72	105.84	106.60	105.92	109.50	109.23	108.64	
k_3	104.80	108.46	104.99	106.86	108.58	107.00	105.20	105.17	106.18	106.69	105.72	
k_4	106.40	99.01	104.78	104.24	105.08	105.74	106.78	107.15	101.14	102.22	101.06	
R	3.26	10.94	2.27	2.94	8.40	4.32	4.09	4.85	8.36	7.02	7.58	

As shown in Fig. 5, the photoelectric switches are used for triggering capacitor bank circuit and measuring the muzzle velocity of the armature. At the muzzle, the distance between two photoelectric switches is 50 mm. When the armature passes the first photoelectric switch, it will output a high level because the beam is blocked. Then, when the armature passes the second photoelectric switch, a high level will be output again. So, according to the time interval between two high levels, the muzzle velocity of the armature can be calculated. For the prototype of three-stage SICG, the current waveform in three drive coils is displayed on the oscilloscope, as shown in Fig. 6 (a). From Fig. 6 (b), the time interval between two high levels is 700 μs, so the muzzle velocity of the armature is 71.4 m/s. Moreover, for the optimized SICG, the current waveform in three drive coils is displayed on the oscilloscope, as shown in Fig. 7 (a). As shown in Fig. 7 (b), the time interval between two high levels is 600 μs, so the muzzle velocity of the armature is 83.3 m/s. Therefore, the energy conversion efficiency of the system is increased by 36.1 % after parameter optimization.



(a) Current waveform in three stages

(b) Velocity of the armature waveform

Fig. 4. Results of calculation.

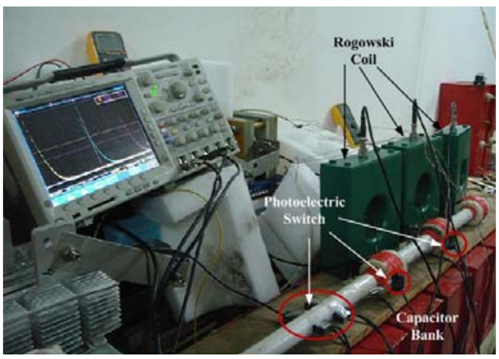
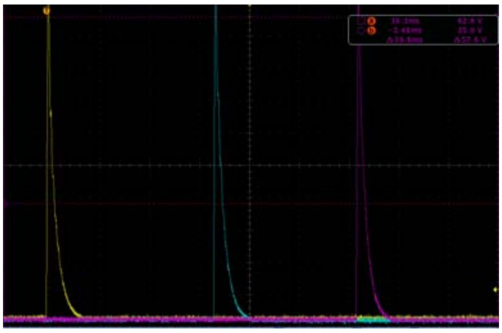
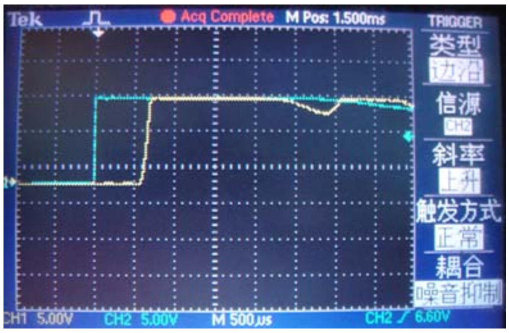


Fig. 5. Experimental system.

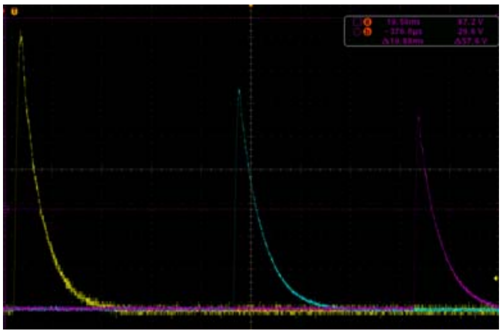


(a) Current waveform

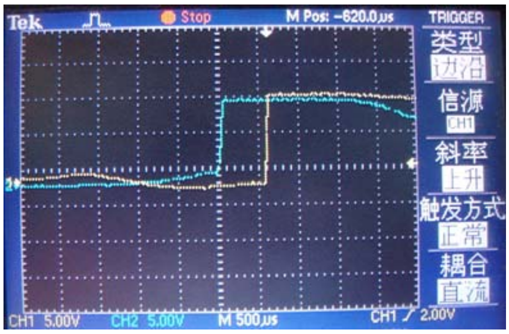


(b) Time interval between two high levels

Fig. 6. Waveform displayed on the oscilloscope for the prototype.



(a) Current waveform



(b) Time interval between two high levels

Fig. 7. Waveform displayed on the oscilloscope for the optimized one.

The results of simulation and experiment for the prototype and optimized one are listed in Table 2. We can find that for the simulation and experiment although the efficiency improvement of two models is approximate, the muzzle velocity of armature is so different. We analyze that the reasons are as follows:

1) Under the constraints of our experimental condition, the measuring muzzle velocity is actually the average value in the measuring distance. Therefore, the measuring value is smaller than actual value.

2) During the testing process, the body of coilgun launcher is arranged horizontally, so the friction between armature and barrel will affect the muzzle velocity of armature. However, the friction was not taken into account in simulation.

In simulation, it is assumed that the armature and drive coils are completely coaxial, but in actual experiment, it is impossible.

6. Conclusion

To optimize the system of a three-stage SICG, the simulations of different system with different parameters are arranged by using orthogonal test approach in this paper. Then, the current filament method is employed to calculate the energy conversion efficiency. Because the mass of armature and the voltage and total capacitance are constant, the muzzle velocity of armature is regarded as the target function, while the capacitance of each capacitor bank, the structural parameters of each drive coil, and the trigger discharge position in each stage are regarded as variables. Using the proposed methodology, the best parameters' condition is obtained. To validate the results of the optimization, the experiments of prototype SICG and the optimized one are conducted respectively. It indicates that the energy conversion efficiency is improved after parameter optimization. In the future work, the presented simulation and optimization method may be applied to the design of a multi-stage coilgun.

Acknowledgements

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