Simulation and Analysis of Electromagnetic Coilgun

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Abstract. This paper presents a method based on Current Hoop Model for the analysis and design of induction coilgun. The cylindrically symmetric armature is subdivided into concentric hoops with diverse rectangular cross-sections, in each of which the current is assumed to be uniform. An equivalent analytical model considering mutually coupling of coils and armature hoops is constructed for dynamic simulation of the coilgun. The circuit equations are solved together with the equation of motion of projectile by using the Treanor method to ensure the convergence. Comparison with the experimental results and the numerical results simulated by Finite Element method (FEM) shows the validity of the presented simulation method for coilgun. The optimization of a six-stage coilgun is achieved by employing the genetic algorithm (GA). It is suggested that the presented algorithm obtains a higher muzzle velocity.

Keywords: Electromagnetic coilgun, equivalent analytical model, genetic algorithm.

1 Introduction

Various types of electromagnetic coilguns have attracted much interest recently because they possess the advantages of the distribution of mechanical stresses that makes them possible to accelerate heavy projectiles, and the absence of current-carrying contact between barrel and projectile that increases the survivability of the barrel. Ronald J. Kaye[1] discussed issues concerned with coilgun design and control. A simplified field-based physical model of coilgun is developed by G. W. Slade[2]. J. L. He, et al.[3] presented a cylindrical current sheet model for the analysis and design of induction type coilgun. Simulated Annealing method is applied to optimization of coilguns by G. Hainsworth and D. Rodger[4]. Seog-Whan Kim, et al.[5,6] designed the single stage and multistage coilgun by employing the genetic algorithm.

2 Equivalent analytical Model

2.1 Establishment of the equivalent analytical model

The coilgun consists of a moving conductive sleeve and driver coils fixed on the barrel. The capacitor bank is connected to the coils as an energy source. The switches are turned on and off in control sequence, the transient magnetic field is established inside the barrel and eddy currents are induced on the surface of the conductive sleeves. The projectile is accelerated by the electromagnetic force produced by the interaction between the traveling magnetic field and the eddy currents in the sleeve. Fig. 1 shows the structure of a capacitor-driven inductive coilgun.[7]

Since the driving coils can be regarded as stranded conductors, the current distribution can be assumed to be uniform. Due to skin-effect, the distribution of eddy currents in the sleeve is not uniform. Fig. 2 shows the current hoop model of the armature, i.e. projectile. The armature is approximated as a collection of rectangular cross-section hoops, whose number and geometry are determined to achieve sufficient precision of the current density distribution. The current density is uniform in any hoop. It is similar to the slingshot package for coilgun simulation. And mutual inductances of hoops are also considered. The inductances of the equivalent circuit are calculated by using the Neumann Formula. The equivalent circuit for this system is shown in Figure 3. The circuit equations and the equation of motion of the projectile can be seen as Equ. (1).

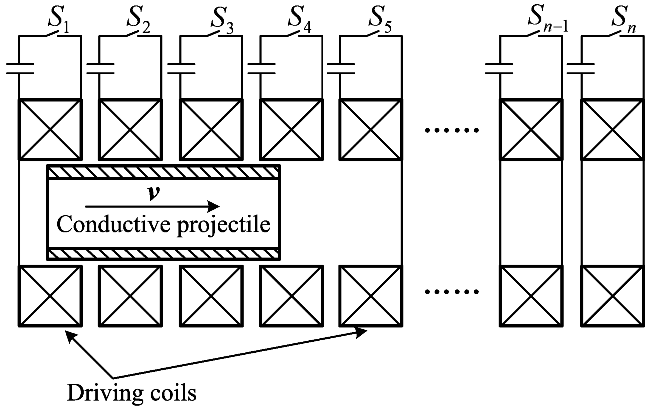

Fig. 1. Structure of a capacitor-driven coilgun

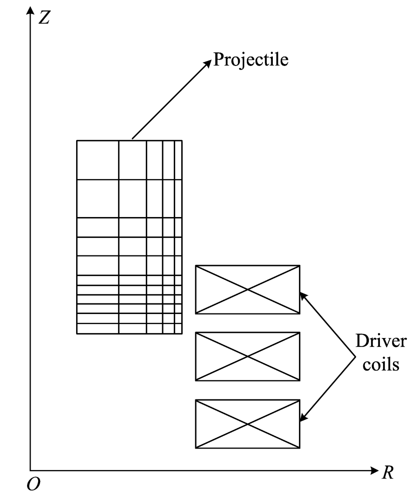

Fig. 2. Current hoop model of armature

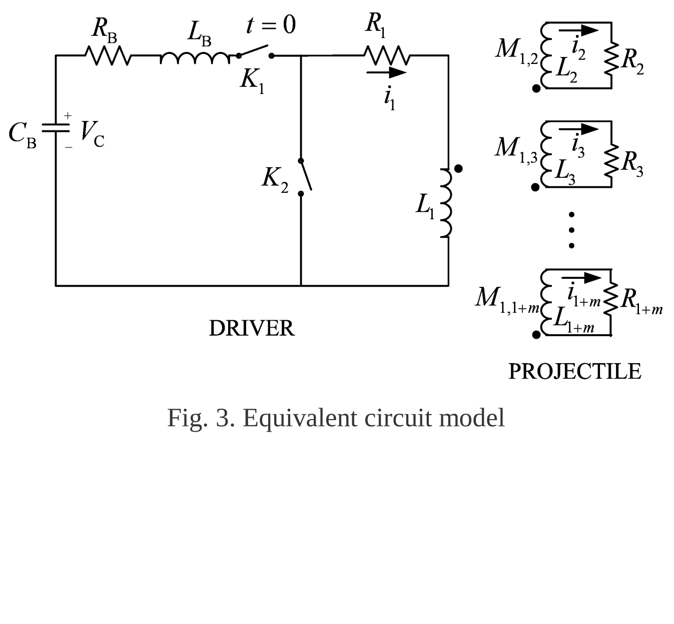

Fig. 3. Equivalent circuit model

$$\begin{cases} [\boldsymbol{L}+\boldsymbol{M}]\dfrac{d\boldsymbol{i}}{dt} = \boldsymbol{V}_C - \boldsymbol{R}\cdot\boldsymbol{i} - v\cdot\dfrac{d\boldsymbol{M}}{dx}\cdot\boldsymbol{i} \\ \boldsymbol{C}\dfrac{d\boldsymbol{V}_C}{dt} = -\boldsymbol{i}_d \\ M_P\dfrac{dv}{dt} = \sum_{p=1}^{m}\sum_{d=1}^{n} i_p i_d \dfrac{dM_{pd}}{dx},\ p=1,2,\cdots m, d=1,2,\cdots,n \\ \dfrac{dx}{dt} = v \end{cases} \tag{1}$$

where $\boldsymbol{L}$ and $\boldsymbol{M}$ are self- and mutual inductance matrices of driver coils and sleeve, respectively. $\boldsymbol{V}_c$ is the voltage of capacity bank. $\boldsymbol{i}$ is a vector of currents flowed in driver coil and hoops in sleeve. M_p、 v and x are the mass、velocity and position of the projectile, respectively. Equ. (1) is solved by using the Treanor method.[8]

2.2 Inductances calculation of the equivalent circuit

2.2.1 Mutual inductance between two hoop curcuits

The mutual inductance between two hoop curcuits can be calculated by Equ. (2).

$$M = \frac{n_1 n_2 \mu_0}{4\pi}\oint_{l_1}\oint_{l_2}\frac{\mathrm{d}l_1\mathrm{d}l_2}{r} \tag{2}$$

where n_1 and n_2 are the turns per unit of length, respectively. l_1 and l_2 are perimeters of the coils, respectively. r is the distance between dl_1 and dl_2.

When the two hoops are coaxial and parallel, the mutual inductance can be calculated by Equ. (3).

$$M = \mu_0 n_1 n_2 \int_0^{\pi}\frac{R_1 R_2\cos(\varphi)}{\sqrt{R_1^2+R_2^2+h^2-2R_1R_2\cos(\varphi)}}\mathrm{d}\varphi \tag{3}$$

where R_1 and R_2 are the radiuses of hoops, respectively. h is the distance between two centres of the hoops. φ is the intersectant angle between dl_1 and dl_2.

2.2.2 Mutual inductance of single solenoid

Fig.4 shows two coaxial solenoids: the right one is the stationary driver coil while the left one is the moving armature. O is set as origin. Mutual inductance between solenoids with lengthes of $2l_1$ and $2l_2$ can be calculated by Equ. (4).

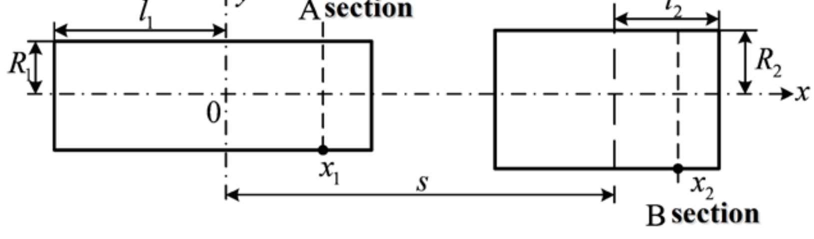

Fig. 4. Mutual inductance of single solenoid

$$M=\mu_0 n_1 n_2\int_0^{\pi}\frac{R_1^2R_2^2\cos(\varphi)}{R_1^2+R_2^2-2R_1R_2\cos(\varphi)}(\sqrt{R_1^2+R_2^2+(s+l_2+l_1)^2-2R_1R_2\cos(\varphi)}$$
$$-\sqrt{R_1^2+R_2^2+(s+l_2-l_1)^2-2R_1R_2\cos(\varphi)}+\sqrt{R_1^2+R_2^2+(s-l_2-l_1)^2-2R_1R_2\cos(\varphi)} \qquad (4)$$
$$-\sqrt{R_1^2+R_2^2+(s-l_2+l_1)^2-2R_1R_2\cos(\varphi)})\mathrm{d}\varphi$$

where n_1 and n_2 are turns per unit of length with the same direction as s. The distance between A and B can be calculated by $h=s-x_1+x_2$. s is the distance between the centres of the solenoids. R_1 and R_2 are radiuses of sections of the solenoids. x_1 and x_2 are two random points on solenoids.

It suggests that a triple definite integral is changed into four integrals during the process of calculation, so that the complexity of calculation is reduced.

2.2.3 Self inductance of single solenoid

On the conditions of R_1=R_2, n_1=n_2=n, 2l_1=2l_2=l and s=0 that self inductance of single solenoid can be calculated by Equ. (5).

$$L=\mu_0 n_1 n_2\int_0^{\pi}\frac{\sqrt{2}R^2\sin^2(\varphi)}{1-\cos(\varphi)}(\sqrt{R^2+2l^2-R^2\cos(\varphi)}-R\sqrt{1-\cos(\varphi)})\mathrm{d}\varphi \qquad (5)$$

It suggests that the calculation of self inductance is simpler than that of mutual inductance.Code for mutual inductance can also be used to calculate self inductance that the complexity of simulation will be reduced.

2.3 Simulation results and analysis

The coilgun prototype designed by Sandia Laboratory, USA, is simulated by the equivalent analytical model and finite element method respectively. The main parameters and simulation results are shown in Table. 1.

Table 1
Parameters and simulation results

Stage		I	II	III	Ⅳ	V	Ⅵ
Capacitance (μF)		20485	5863	2059	1683	835	684
Voltage (kV)		4.6	9.1	14.7	16.3	19.7	20.3
Muzzle velocity (m/s)	Experiment	80	145	226	274	307	335
	FEM	87.29	151.11	222.65	263.23	304.47	328.83
	Analytical model	87.33	150.58	219.13	259.03	299.51	323.11
	Error_A&E(%)	9.16	3.85	-3.04	-5.46	-2.44	-3.55
	Error_A&F(%)	0.04	-0.35	-1.58	-1.59	-1.63	-1.74
Peak current (kA)	Experiment	30.8	31	43.7	40.7	41.3	41.5
	FEM	32.8	37.32	34.03	38.53	31.15	32.39
	Analytical model	33.06	37.71	34.99	39.16	33.32	33.35
	Error_A&E(%)	7.34	21.65	-19.93	-3.78	-19.32	-19.64
	Error_A&F(%)	0.8	1.05	2.83	1.63	6.95	2.95

Note: Error_A&E stands for relative error between the results of analytical model and the experiment. Error_A&F stands for relative error between simulation results of analytical model and FEM with Ansoft.

Error_A&F of muzzle velocity is less than 2% while that of peak current is less than 7%, so that the validity of the analytical model is verified. Error_A&E of muzzle velocity is less than 6% except the first stage which may be beacause that the initial position of the projectile is unknown in the experiment. Error_A&E of peak current is irrational that the current from the driver coil is not DC, so the resistances of the driver coils should be modified.

3 Optimization of Six-stage Coilgun

The genetic algorithm, coupled with equivalent analytical model, is used for optimization of a six-stage coilgun, which is made by Sandia Laboratory, USA. The genetic algorithm is based on evolution procedure through generations. The evolution consists of three steps: reproduction, crossover and mutation.[9]-[10] The design variables for optimization are chosen as the turn numbers of each coil, distances between adjacent driver coils, coil trigger positions of all the stages. The objective function is to achieve the maximum of muzzle velocity. The optimal design results of the coilgun are shown in Table 2.

Table 2

The optimal design results of the six-stage coilgun

Stage	I	II	III	IV	V	VI
Axial turn number of coils	13	18	16	24	13	22
Radial turn number of coils	3	3	3	2	2	2
Distance between driver coils(m)	0	0.0324	0.0772	0.06082	0.03877	0.06208
Trigger position (m)	0.05244	0.12613	0.21383	0.37954	0.60061	0.68512

The velocity, force as well as position of projectile and current flowing in driver coils simulated with the optimized parameters by FEM and the equivalent analytical model are shown in Figs. 5 to 8, respectively. It suggests that the optimization results are in good agreement with FEM. The muzzle velocity simulated by the equivalent analytical model reaches 356.25 m/s compared with the former result 323.11 m/s.

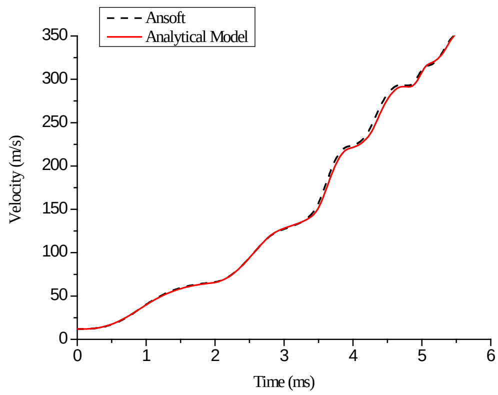

Fig. 5. Velocity of projectile after optimization

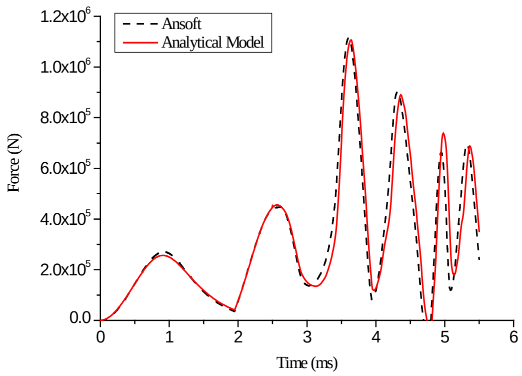

Fig. 6. Force of projectile after optimization

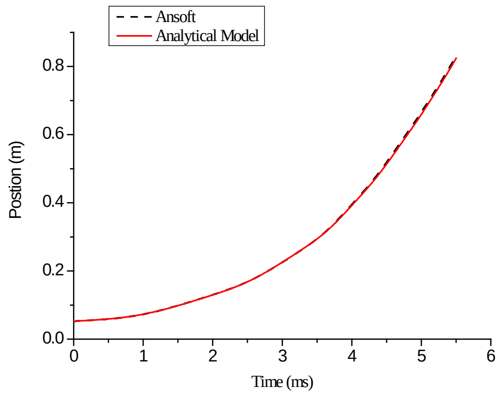

Fig. 7. Position of projectile after optimization

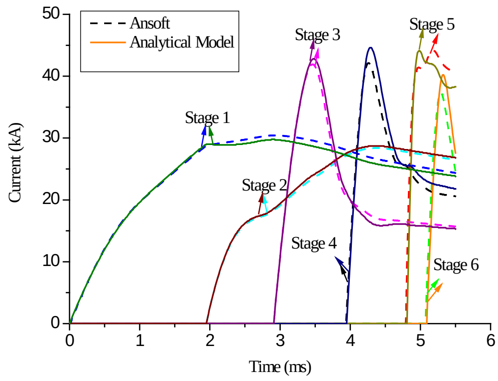

Fig. 8. Current flowing in driver coils after optimization

4 Conclusion

This paper presents the transient simulation and optimization for the capacitor-driven inductive coilgun. A method based on Current Hoop Model is adopted for accurate eddy current calculation. An equivalent analytical model is established to simulate the dynamic performance of coilgun. The simulated results are verified by FEM with Ansoft and experiment results. The optimization of coilgun is achieved by using genetic algorithm and the optimization results are in good agreement with FEM. By the comparison between the optimized results and the original model, it can be concluded that the muzzle velocity can be increased. In the future work, the presented model and optimization method may be applied to the design of multi-stage coilgun and the time for optimization might be shorter.

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