The Geometry Optimization Design of a Rectangular Cross-sectional Rail Launcher

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Abstract. The conclusion that geometry、quality of the armature、initial charging voltage of the capacitor and capacitance size are the main factors which influence the system performance of a rectangular cross-sectional rail launcher is got by studying of the literature. A mechanical model and electromechanical model are built in this paper. Both the Artificial fish-swarm algorithm (AFSA) and Particle Swarm Optimization (PSO) are imported to optimize the system for rail geometry. The experiment results show that the conclusions obtained by two methods are close which shows the veracity and practicality of this method. This paper can provide certain reference for the design of a rectangular cross-sectional rail launcher.

Introduction

Since the successful test in 2007 huge kinetic energy electromagnetic rail launcher, the rail launcher gradually aroused people's concern with its various performances which is much better than conventional weapons, many countries began to realize its potential and working hard on it.

We can get the conclusion that geometry、quality of the armature、initial charging voltage of the capacitor and capacitance size are the main factors which influence the system performance of a rectangular cross-sectional rail launcher by studying of the literature. Increasing the quality of the armature will reduce the muzzle velocity, which will certain have an effect on muzzle kinetic energy, however, the quality of the armature is varied in practical application, it is depended on the mission. And the muzzle velocity will benefit from either the increase in initial charging voltage of the capacitor or capacitance size, however, In terms of the current power supply technology development situation, the greater the initial charging voltage of the capacitor is, the capacitor is more vulnerable to be damaged. Reference [1] points out that rail geometry denotes many impacts on inductance gradient , there by has an influence on system performance , so that the research on rail geometry has certain significance.

The paper is organized in the following sequence. In Section 1, both mechanical model and electromechanical model are built, and the related mathematical derivation is shown. In Section 2, the method of AFSA and PSO is introduced and realized. In Section 3, numerical simulation results are made and given to demonstrate the validity of the model. Concluding remarks are summarized in the final section.

The mathematic model for a rectangular cross-sectional rail launcher

Rail-gun is based on *Ampere's law* which is shown in fig.1.

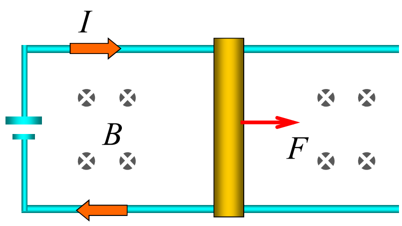

Fig. 1. A simple rail launcher

As we can see from Fig. 1,when system is running, current(I) inflows by the side of the rail and through the armature after back from the other side, the Ampere force which is generated by magnetic fields between two rails of effects on the armature makes the armature move along the straight rail. Reference [2] gives a model of the system and the force on armature is calculated as Eq.1, which came from the point of view of conservation of energy.

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

Here I、 L' for the current intensity and inductance gradient respectively. By using the principle of current sheet, the inductance gradient (L') can be calculated as follows:

$$L' = \frac{2s\mu_0}{\pi wh} \int_{0.5s}^{0.5s+w} \tan^{-1} \frac{x\mathrm{h}}{y\sqrt{4y^2+4x^2+h^2}} dy \tag{2}$$

Here w、 h、 s for the width、 height and the track spacing between two rails respectively.

For the reasons that the speed grows too fast in the system of rail launcher, air resistance and frictional resistance can not be ignored, Reference [3、4] gives the model of air resistance and frictional resistance as below:

$$F_k = 1.1\rho_0 hsv^2 \tag{3}$$

$$F_f = \mu_f \left(F_0 + \frac{l_d}{s} \frac{L' I^2}{2} \right) \tag{4}$$

Here $\rho_0 = 1.29 kg/m^3$ for the density of air at standard atmospheric pressure,v for speed of armature. μ_f 、 l_d for the coefficient of friction and the length of rail respectively.

Combining formula (1)、(3)、(4) and using Newton's second law, the resultant force on the armature is:

$$F = F_E - F_f - F_k = ma \tag{5}$$

The equivalent circuit for capacitor drived rail launcher system is shown in Fig.2. Energy stored in capacitor begins to discharge through rails in the initial value of $Uc(t)$ when switch S is closed, $R(t)$ ant $I(t)$ shows they are time- variable, with the moving of armature, the resistance and inductance is changing, $E(t)$ for counter electromotive force[5].

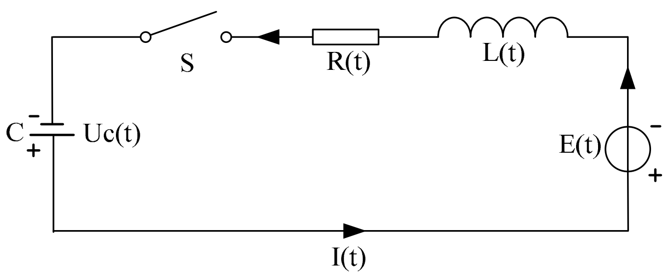

Fig.2 The equivalent circuit for capacitor drived rail launcher system

The circuit equation of capacitor drived rail launcher system can be derived as below according to the Kirchhoff's law .

$$E(t) + R(t)I(t) + \frac{d}{dt}[L(t)I(t)] = U_c(t) \tag{6}$$

$$I(t) = -C\frac{dU_c(t)}{dt} \tag{7}$$

$$E(t) = \frac{1}{2} C L^{'} v \frac{dU_c(t)}{dt} \tag{8}$$

Combining formula (6)、(7)and(8), a second order differential equation is got about capacitor voltage.

$$CL(t)\frac{d^2U_c(t)}{dt} + U_c(t) + C(R(t) + 1.5Lv^{'})\frac{dU_c(t)}{dt} = 0 \tag{9}$$

The initial conditions of the equation before are:

$$\begin{cases} U_{c0} = U_c(0_+) = U_c(0_-) \\ \dfrac{dU_c(t)}{dt}|_{t=0_+} = I(0_+) = I(0_-) = 0 \end{cases} \tag{10}$$

There are three kinds of states for this two-order system ,which contains under damped state 、over damping state and critical damping state. According to the actual situation, this paper only considers under damped state. System has a pair of complex conjugate roots in this state, Capacitor voltage and current can be calculated as below:

$$\begin{aligned} U_c(t) &= U_{c0} e^{K_1 t} (\cos K_2 t - \frac{K_1}{K_2} \sin K_2 t) \\ I(t) &= C U_{c0} e^{K_1 t} \sin K_2 t (K_2 + \frac{K_1^{\ 2}}{K_2}) \end{aligned} \tag{11}$$

In which, K1 K2 can be calculated like this:

$$\begin{aligned} K_1 &= -\frac{R^{'}}{2L^{'}} - \frac{3v}{8x} \\ K_2 &= \sqrt{\frac{1}{2CL^{'}x} - K_1^{\ 2}} \end{aligned} \tag{12}$$

Optimization design methods and results

The optimization model mainly includes objective function and constraint conditions, we set muzzle velocity as the objective function and the rail geometry as constraint condition.

$$\begin{cases} MAX\ f(h,s,w) = v \\ (h,s,w) \in [a,b] \end{cases} \tag{13}$$

Here, $[a,b]$ for the range of rail geometry.

We can get the result by using AFSA and PSO which is shown in table 1. Constraint condition is $a = 0.03\text{m}$ 、 $b = 0.1\text{m}$.

Table 1 the result of AFSA and PSO

parameter	AFSA result	PSO result	parameter	AFSA result	PSO result
track spacing（m）	0.0476	0.0468	muzzle velocity(m/s)	1536.8127	1537.3609
heigh（m）	0.0308	0.0300	system efficiency	0.1196	0.1230
weigh（m）	0.0307	0.0300	launch efficiency	0.1400	0.1414

As we can see from table 1, the final muzzle velocity is about 1536.8m/s(1537.4m/s), and the muzzle kinetic energy is 29523J(29543J). The point that launch efficiency is greater than system efficiency is approved too. To follow the progress of AFSA and PSO, we show 20 times iterative process in the process of calculation, which is shown in Fig.3 and Fig.4 .

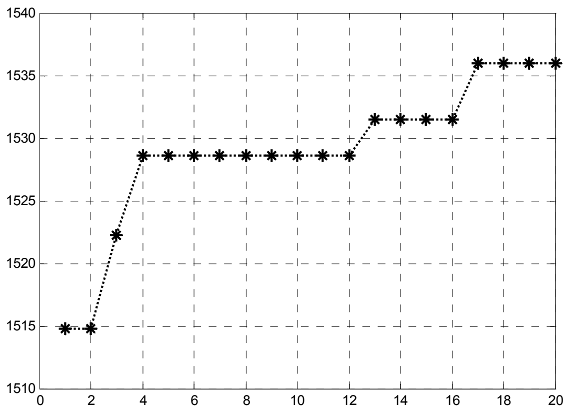

Fig. 3. The progress of AFSA

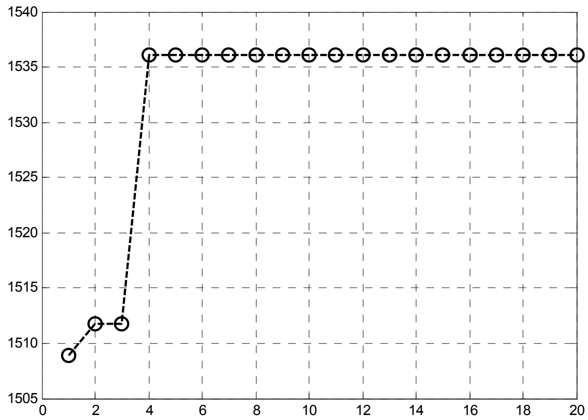

Fig. 4. The progress of PSO

Comparison and analysis of the result

Both the AFSA and PSO have a similar conclusion, which shows the veracity and practicality of this method. but Fig.3 and Fig.4 shows that AFSA takes more time than PSO in each optimization process, so we take example for PSO below, table 2 shows the performance comparison before and after optimization. The reult shows that muzzle velocity has an improvement of 3.45% and launch efficiency falls 13.57%, which means the system is good for speed increase after optimization but this increasement is in the precondition of sacrificing launch efficiency.

Table 2 Before and after optimization

Comparison	Before	After（Upgrade %）
muzzle velocity(m/s)（m/s）	1486.2	1537.3609 (3.45%)
launch efficiency(%)	16.36	14.14(-13.57%)

Conclusion

The mathematical model of railgun system is derived in this paper, which was considered as the basis of the next step work. Both the Artificial fish-swarm algorithm (AFSA) and Particle Swarm Optimization (PSO) are imported to optimize the system for rail geometry. Some numerical simulations have demonstrated the validity and capability of the proposed optimization design in this paper.

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