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A Measuring Method About the Bullet Velocity in Electromagnetic Rail Gun

Jianming LIU, Zhiyong BAO, Yang LIU, Zhenchun WANG, Fucai LIU
College of Electrical Engineering, Yanshan University,
Qinhuangdao, 066004, China
E-mail: ppkkkk@126.com

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Abstract: The operating principle of electromagnetic rail gun by store capacitor was analyzed. A simulation model about the bullet velocity in the electromagnetic rail gun was built. The results of computer simulation experiment showed the relationships between the bullet velocity and the capacitor charging voltage and the pellet mass. By ten coil targets, a new kind of measuring method for the bullet velocity in electromagnetic rail gun was presented. The results of the actual experiment were analyzed. The improving method for measuring bullet velocity was put forward. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Bullet velocity, Electromagnetic induction, Velocity measurement, Store capacitor, Electromagnetic rail gun.

1. Introduction

Instead of relying on an explosive propellant such as gunpowder, the electromagnetic rail gun uses a giant surge of electrical energy to fire the bullet [1]. A rail gun is an electromagnetic projectile launcher based on similar principles to the electromagnetic motor [2]. Qingguo Chen established the computer simulation model of a rail gun [3] and described the electromagnetic process of firing an armature bullet. Hui Zhao analyzed the measuring process of the armature bullet velocity. In this paper, by energy storage capacitor [4], the model of the armature bullet velocity was established [5]. The simulation model of Simulink software was designed. The relationships between the bullet velocity [6] and the charging voltage of the capacitor and the armature pellet mass were analyzed. The simulation experiment of the armature bullet velocity was designed [7]. The flight trajectory of the armature bullet was recorded by sensor devices [8, 9]. By measuring the time interval between the armature bullet pass through the two sensor devices, the armature bullet velocity can be calculated. A measuring system with ten coil targets is designed to measure armature bullet velocity.

2. Working Principle of Rail Gun

The electromagnetic rail gun is designed based on the working principle of that current is affected by the magnetic field [10]. The bullet as an armature is placed on the two parallel rails. The current is inputted from a rail, passing through the armature bullet, and then it is outputted by another rail. The armature bullet as a current carrying conductor is accelerated along the rails. Finally, it is launched out at high speed. When the accelerated armature bullet is cutting magnetic lines in the magnetic field, the armature bullet is added a thrusting force.

$$F(t) = B(t)I(t)l , \tag{1}$$

where $F(t)$ is the force acting on the bullet. $B(t)$ is the magnetic induction intensity. $I(t)$ is the armature current. l is the interval between the two rails. The principle diagram of the electromagnetic rail gun is shown in Fig. 1.

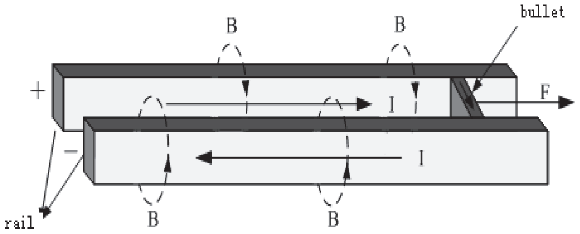

Fig. 1. The principle of rail gun.

The magnetic induction intensity is proportional to the armature current. The force acting on the armature bullet is proportional to product on the magnetic induction intensity and the armature current. If m is the mass of the armature bullet, the force acting on the armature bullet is:

$$F(t) = ma(t), \tag{2}$$

There are three methods to increase the velocity of the armature bullet: 1) To increase the intensity of the magnetic induction, the current in the guide rails is increased. 2) The interval between the two rails is increased. 3) The length of rail is increased.

3. Equivalent Circuit of Rail Gun

The emission process of the electromagnetic rail gun involves electromagnet, current, friction and so on. In order to find out the relationships between the armature bullet velocity and the voltage and the armature bullet mass, some influencing factors are ignored. Some simplifications and assumptions are made as follows: 1) The armature bullet is in close contact with the rails. 2) The friction between the armature bullet and rails is ignored. 3) The air resistance to the armature bullet is ignored. 4) Two rails are absolute parallel. 5) The current is stable change. 6) The skin effect of the current is ignored. The equivalent circuit of the electromagnetic rail gun is shown in Fig. 2.

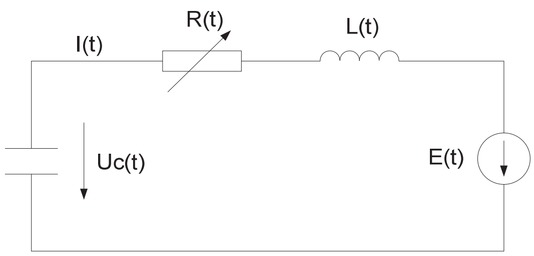

Fig. 2. The simplified equivalent circuit.

$E(t)$ is the back electromotive force generated by the armature bullet. $Uc(t)$ is the voltage of the energy storage capacitor. $I(t)$ is the current in the rail circuit. $R(t)$ is the equivalent total resistance of two rails. $L(t)$ is the equivalent total inductance of the loop. The simplified circuit diagram is:

$$\begin{aligned} Uc(t) - E(t) &= R(t)I(t) + \frac{d}{dt}\left[L(t)I(t)\right] \\ &= R(t)I(t) + L(t)\frac{dI(t)}{dt} + I(t)\frac{dL(t)}{dt} \end{aligned}, \tag{3}$$

Because the magnetic intensity is proportional to the current, the force acting on the armature bullet is proportional to the square of the current. Combining with the formula (1) to (3), the force acting on the armature bullet is:

$$F(t) = ma(t) = k_F I^2(t), \tag{4}$$

where k_F is the coefficient related proportion. Because the armature bullet is much smaller than the diameter of the length of the rail, k_F ($=4\times10^{-7}$[3]) is used as the constant. By formula (1) to (4), the relationship between the current and the voltage is:

$$v(t) = v_0 + \frac{K_F}{m}\int_0^t I^2(t)dt, \tag{5}$$

where $v(t)$ is the velocity of the armature bullet. v_0 is the initial velocity of the armature bullet. x_0 is the initial position of the armature bullet. The position of the armature bullet is:

$$x(t) = x_0 + v_0 t + \frac{K_F}{m}\int_0^t\int_0^t I^2(t)dtdt, \tag{6}$$

The inductance of the rails is:

$$\frac{dL(t)}{dt} = L_0\left[v_0 + \frac{K_F}{m}\int_0^t I^2(t)dt\right], \tag{7}$$

where L_0 is the inductance of the per unit length of the rail. $L(t)$ is the inductance of the launching rails. When the moving armature bullet cuts the magnetic line, the electromotive force $E(t)$ is:

$$E(t) = B(t)v(t)l, \tag{8}$$

where $B(t)$ is the magnetic induction intensity. $v(t)$ is the armature bullet velocity. $E(t)$ is proportional to $v(t)$. $B(t)$ is proportional to $I(t)$.

$$E(t) = K_F I(t)\left[v_0 + \frac{1}{m}\int_0^t K_F I^2(t)dt\right], \quad (9)$$

The relationship between the electromotive force $E(t)$ and $I(t)$ is presented in above equation.

4. Simulation Circuit of Bullet Velocity

According to above formulas, the relationships between the armature bullet velocity and the armature pellet mass and the capacitor voltage are fitted. The simulation circuit of the armature bullet velocity designed by Simulink software is shown in Fig. 3.

5. Simulation Experiment

The simulation experiment is used as guidance to the actual experiment. According to above formulas and circuits, some simplifications and assumptions are made as follows: 1) The values of the inductance and the resistance are fixed. 2) The values of the inductance and the resistance are largest while the armature bullet is at the enf of the electromagnetic rail gun. 3) The initial velocity of the armature bullet is zero. 4) The charge and the discharge of the capacitor are smooth.

We select that the armature bullet mass is 18 g. When the capacitance value is respectively 5000 μf , 8000 μf and 10000 μf , the output results of the simulation experiment are respectively obtained. The relationships between the armature bullet velocity and the charging voltage of the capacitor are shown in Fig. 4. The relationships between the armature bullet velocity and the armature bullet mass are shown in Fig. 5.

Some rules are discovered by the output results of the simulation experiment. 1) When armature bullet mass reaches a certain value, the armature bullet velocity will be very small. 2) The armature bullet velocity is decreased while the armature bullet mass is increased. 3) The armature bullet velocity is increased while the voltage of capacitor is increased. Because the resistance and the friction are ignored, the simulation outputs of the armature bullet velocity are larger than real data.

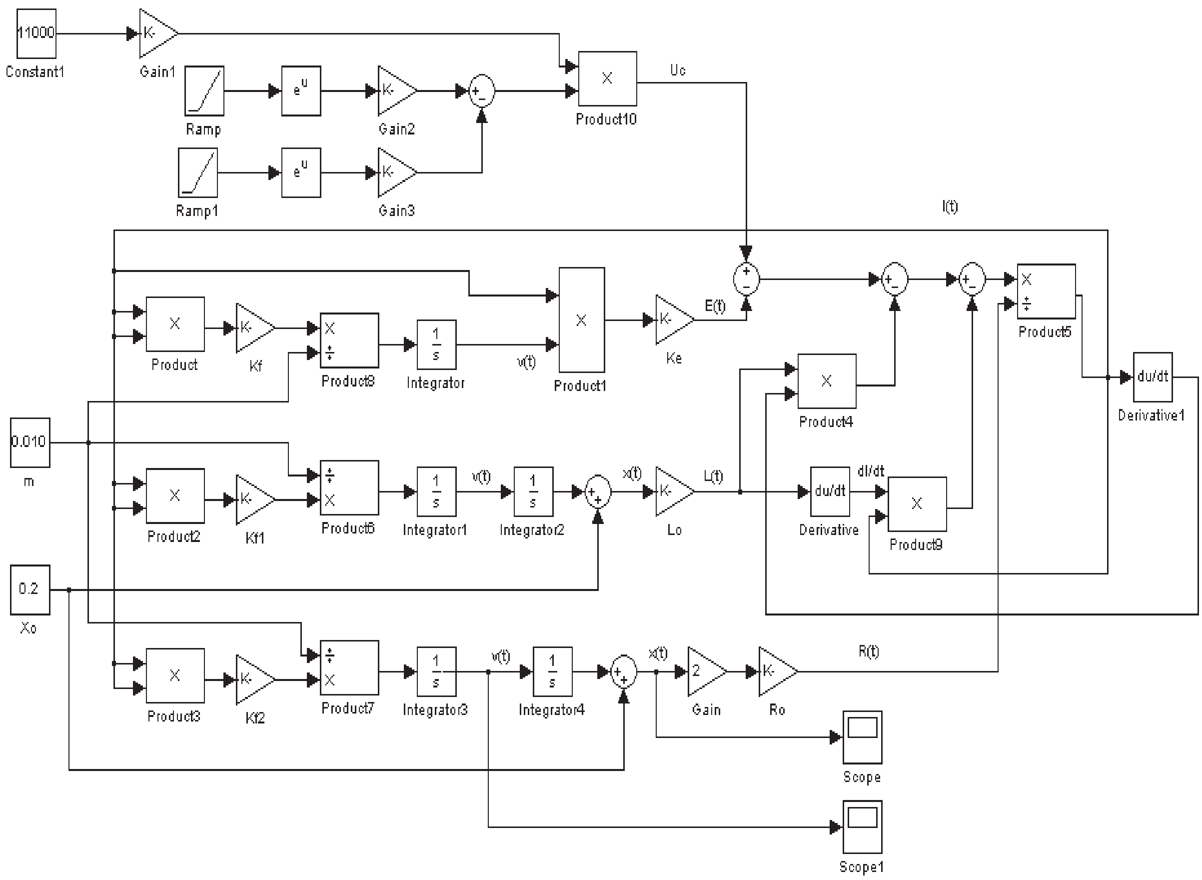

Fig. 3. The simulation circuit of bullet velocity.

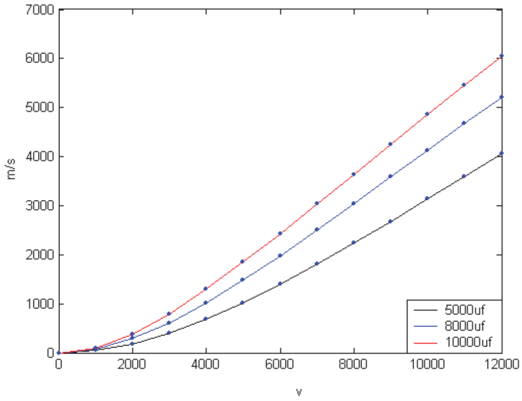

Fig. 4. Relationships between the velocity and the voltage.

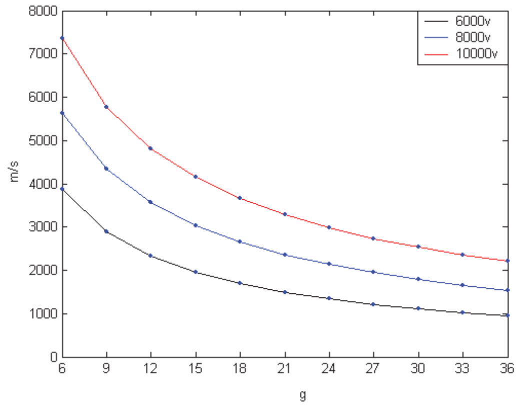

Fig. 5. Relationships between the velocity and the mass.

6. A Measuring Method of Bullet Velocity

The armature bullet velocity can be measured by the induced electromotive force. The electromotive force is generated while the armature bullet cutting the magnetic field. The ten coil targets as measuring device are placed along the electromagnetic rail with the equal distance. When the armature bullet passes through each coil target, the induced electromotive force e is produced respectively in each coil target. The armature bullet and two guide rails form a loop circuit. The current is run through the armature bullet and two electromagnetic rails. There will be a huge current passing through the armature bullet. When a strong magnetic field is produced by the current, the armature bullet is magnetized. The working principle of measuring bullet velocity is shown in Fig. 6.

The induced electromotive force e is shown in Fig. 7.

The output curve of the induced electromotive force is shown in Fig. 8.

When the armature bullet in orbit is accelerated, the armature bullet moves forward through each coil target. Because of the magnetic flux change, the induced electromotive force is produced in each coil target. The electric pulse is generated by induced electromotive force. In the coil target, the electric pulse is used as opening and closing trigger. The maximum value of the electric pulse is used for measurement. By measuring the time interval of the electric pulse between two coil targets, the time of bullet passing through two coil targets is calculated.

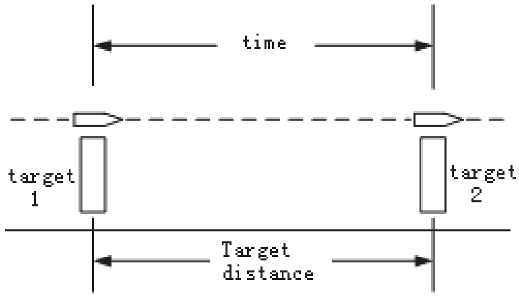

Fig. 6. The measuring method of bullet velocity.

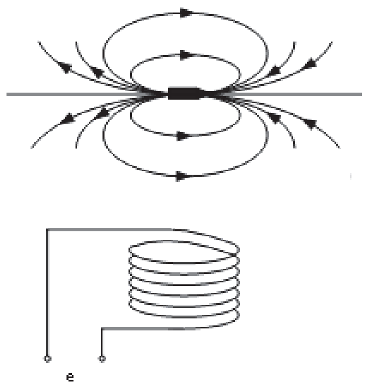

Fig. 7. The electromotive force e is produced.

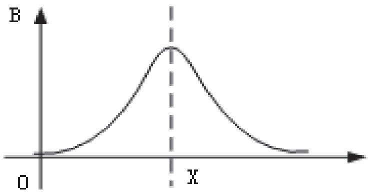

Fig. 8. The output curve of induced electromotive force.

7. Design of Coil Target

The measuring coil is made with insulating sheath enameled wire. The measuring coil target is made by winding the enameled wire in the probe bracket. The induction strength has the relationship with the cross sectional area of single coil and the turns of winding. The induction formula is:

$$B = \frac{\mu_0 n I a^2}{2(a^2 + x^2)^{\frac{3}{2}}}, \quad (10)$$

where n is the turns of winding wire. a is the radius of the coil. The more the turns of winding wire are, the more the inducted magnetic field get. The larger the sectional area of the coil is, the less the inducted magnetic field get. The inducted electromotive force equation is:

$$e = k\frac{dB}{dt}, \tag{11}$$

The cross sectional area of coil is 20 mm. The 25 groups of the turns of winding are used in the coil target. When the induction strength is not uniform, measuring error will be caused. To reduce measuring error, the sectional area or the volume of the coil is reduced. But this time, the measuring sensitivity is decreased. The ten coil targets are placed side by side on the rail bracket.

8. Design of Conditioning Box

The measuring signal generated by induction is very weak. The measuring signal in each coil target is transmitted to a conditioning box by shielded coaxial cable. The amplifying and coupling chips in the conditioning box are shown in Fig. 9.

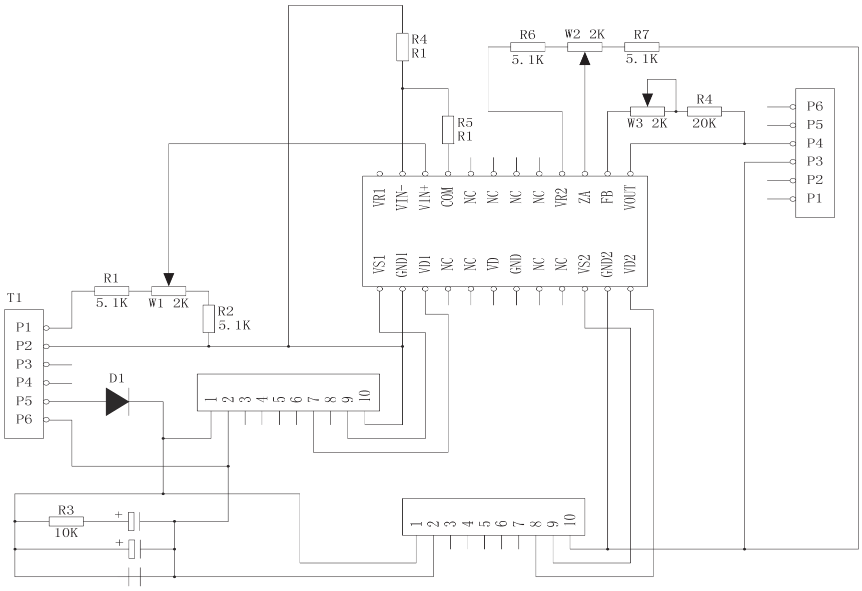

Fig. 9. The coupling and amplifying circuit.

Because the measuring system is in the strong magnetic field environment, the burr interference will appear in the induced voltage signal. Because of long distance transmission, the voltage signal is very easy to be disturbed when it is transmitted in the cable. In order to eliminate the burr and interference signal, induced voltage signal is processed by the designed conditioning box. The isolation amplifying circuit is used to shield voltage signal and eliminate the burr. The amplifying circuit is coupled with R-C filter to eliminate electromagnetic interference and clutter interference. The photoelectric coupler is used to eliminate interference from the system noise and the ground loop.

To protect each respective circuit in the conditioning box, the different power and ground is used in input and output parts. Each circuit in the conditioning box is isolated. After the measuring signal is processed in the conditioning box, it is transmitted to the data acquisition card.

9. Actual Experiment

The actual experiment of the armature bullet velocity is guided by the simulation experiment. The ten coil targets are placed on the electromagnetic rails with the equal distance. The coil target can rapidly measure the armature bullet velocity. By using the designed conditioning box, the electromotive force can be accurately measured by the acquisition system. The actual experimental results of coil target 1 and coil target 2 are shown in Fig. 10.

Above actual experiment of the armature bullet velocity is done repeatedly at the army shooting range for Military. The disturbance waveform of the induced electromotive force is very small. The error of the measurement and transmission is within the required range.

10. Improvement of Experiment

The peak time of the electric pulse in the adjacent coil targets is subtracted to get the interval time of the armature bullet passes through two coil targets. The produced electric pulse in coil target should be consistent (including: its shape, size, delay time, etc.). Otherwise the measuring time of the bullet passes through two coil targets will be inconsistent. It will result in measuring error. If the measuring coil targets are put too close, the interference signal will be generated in the coil targets. The parameters of all coil targets should be the same. The coil targets and two rails should be placed vertically. The interval distance of each coil target is the same.

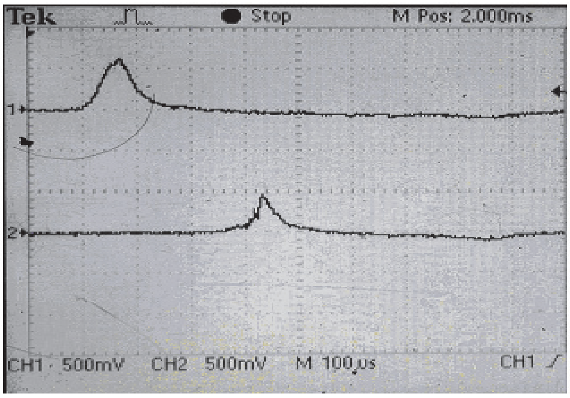

Fig. 10. The actual experimental results.

The conversion rate in amplifying and isolating circuits will cause the converting error. The data acquisition card of 100 M is used in the experiment. When the maximum output value of the produced electromotive force e is just in the middle of two sampling sites, the collecting peak time is not practical peak time. In this time, the maximum error is a sampling interval time.

The induced electromotive force in the coil target is generated by the strong magnetic field. If the magnetic field sometimes is strong and sometimes is weak, it will make the electromotive force peak output forward or backward and result a time error. The burr interference must be eliminated. Otherwise It will generate a lot of peak voltage signal. When there are a lot of peak voltage signal, we cannot identify which voltage signal is true. The coaxial cable with shielding effect should be used in the actual experiment. The working field should be kept away from the interference source of strong magnetic field.

11. Conclusions

According to the principle of the electromagnetic rail gun, an equivalent model of the electromagnetic rail gun is built. The differential equations of the rail gun are established. The simulation experiment of the armature bullet velocity is designed. Some rules are discovered from the output results of the simulation experiment. A new measuring system with ten coil targets is designed to measure the armature bullet velocity. The actual experiments of the armature bullet velocity are done at the army shooting range in Hebei province, China. The output results of the actual experiment are analyzed. The advantages of the new measuring system are as follows: fast speed, simple structure, high precision, easy installation and low cost. It can meet the armature bullet velocity test requirements.

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