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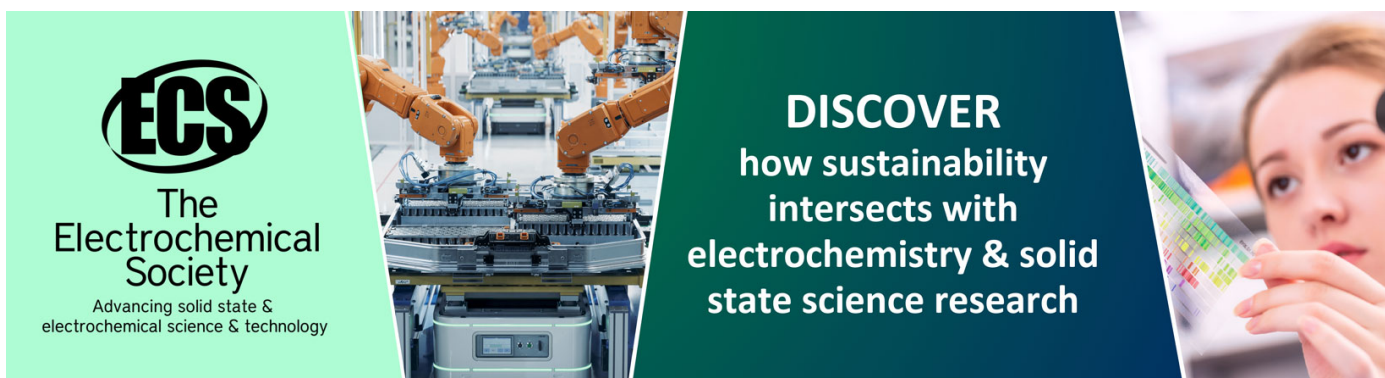
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An initial velocity model study of electromagnetic railgun based on back propagation neural network

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Abstract: The velocity of launch has been the key factor restricting the application of electromagnetic rail. For electromagnetic launch system, the structural parameters change directly or indirectly affect the Launching velocity of the electromagnetic launch system. In order to improve the initial velocity of the electromagnetic railgun. The mathematical model of electromagnetic rail gun launch was set up, the structure parameters of armature and the size of the pretension force between armature and orbital were variables, based on the target function, The equivalent model of rail gun BP neural network is established by using the calculation results of mathematical model, and the model of rail gun BP neural network was optimized by electromagnetic emission test data. The error of rail gun BP neural network model optimized by experimental data is 18.5% lower than that before optimization and 6.5% lower than that of experimental data. The results show that the launch speed of the optimized rail gun BP neural network model is closer to the actual speed.

1. Foreword

Through a series of power conversion systems, the electromagnetic rail gun stores the sustained power energy into the high energy density energy storage system, and then releases it through the linear orbit, accelerating the projectile speed of extremely penetrating and firing out. Be compared to conventional weapons, it has the advantages of extreme initial firing speed, short flight time and good destructive effect. Velocity ejection, muzzle kinetic energy 10.64MJ, electromagnetic launch test was carried out at Dugway test site in 2016, muzzle kinetic energy 3MJ, launch test was carried out at the end of Dahlgren shooting range in 2017, the initial speed of muzzle reached 7242km / h, which can penetrate concrete outside 160km (figure 1). The United States plans to equip the electromagnetic rail gun to a new type of DD (X) stealth destroyer in 2020 / 2025 to meet the requirements of 21 kg in mass, 12 rounds per minute in firing speed, 10000 rounds in life and 300 km in combat distance. At the same time, France and Germany established a semi - Pegasus rail gun system has been developed and tested.

In research of electromagnetic rail gun system, the structural parameter design of the barrel bore is a significant research content of electromagnetic track gun. The inner chamber of the electromagnetic rail gun works under 100 gigabytes to megabits of current, which is the object of the impact of instantaneous



strong pulse current, and is also affected by strong electromagnetic force, heat and high load during launch. At the same time, friction between the armature and track in high speed motion can easily cause track ablation, decrease the initial velocity of muzzle, and the requirements of a system index. Therefore, in the process of electromagnetic track gun tube structure design, the selection of bone structure parameters and the accurate calculation of muzzle initial velocity can improve the design level of electromagnetic track gun and meet the need of electromagnetic rail gun engineering. The requirement of a performance index is of great significance [1-2].



Figure 1. Electromagnetic rail gun in American test.

2. Principle and model of electromagnetic rail gun

The electromagnetic rail gun is made up of two fixed guideways connected to a larger current source in parallel and an armature that maintain good electrical contact with the guideway and can slide along the axis of the guideway (see figure 2). When the power supply is enabled, the current flows through the armature along one guideway and back by the other guideway, thus forming a closed loop. When a strong current flows through two parallel guideways, a strong magnetic field is generated between the two guideways, which interacts with the current flowing through the armature to produce a strong electromagnetic force, which pushes the armature and the projectiles placed in front of the armature to accelerate along the guideway, thus obtaining a high speed. The armature has moved in orbit in the process. The guideway will bear the action of moving dynamic load (electromagnetic tension). When the armature reaches a fixed speed, that is, critical velocity, is impossible produce instantaneous high stress and high strain, which the ablation of the guideway [3-4].

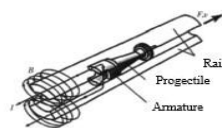


Figure2. Schematic diagram of electromagnetic rail gun.

3. Basic composition and principle of electromagnetic rail gun

3.1. Circuit Equation

The circuit schematic diagram of the track gun system is illustrated in figure 3. The power supply part includes n capacitor discharge modules. Each capacitor discharge module is composed of capacitor discharge branch and continuous current branch in parallel with wave regulating inductor and cable, and the multi-capacitor bank is attached to the rail gun body after parallel connection. As the load divide, the rail gun can be regarded as the resistance and inductance that change with the armature motion. In the process of transmission, there are three situations in the circuit: (1) the switch is turned on and the capacitor begins to discharge, the initial conditions are as follows: the voltage at both ends of the capacitor is charging voltage and the circuit current is zero; (2) in order to avoid the recharging of

capacitor by LRC concussion circuit When the voltage at both ends of the capacitor is reduced to 0V, the current continuation circuit is turned on and the armature is out of the chamber, and the current is rapidly reduced to zero [5-6].

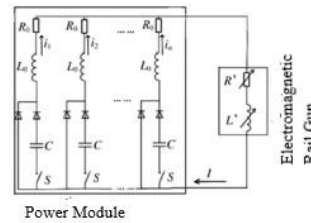


Figure 3. Circuit principle diagram of rail gun system.

According to the Kirchhoff voltage principle, the equation of the rail gun voltage loop is as follows:

$$U_0 = \frac{1}{C} \int i_n(t) dt + i_n(t) R_0 + \frac{di_n(t)}{dt} L_0 + R' X(t) I(t) + L' X(t) \frac{dI(t)}{dt} \quad (3-1)$$

uctance value, R_0 is able and capacitor resistance value, L' is the value of rail gun inductance gradient, R' is the value of rail gun resistance gradient, and U_0 is the value of capacitor charging voltage $i_n(t)$ is the current through the N th power module; $I(t)$ is the current through the rail gun; $X(t)$ is the armature position.

Because of the continuous current loop, when the voltage at both ends of the capacitor is reduced to 0, the voltage at both ends of the capacitor is approximately 0, then the equation of state is as follows:

$$i_n(t) R_0 + \frac{di_n(t)}{dt} L_0 + R' X(t) I(t) + L' X(t) \frac{dI(t)}{dt} = 0 \quad (3-2)$$

The relationship between the current through the rail gun system and the current through each power module is as follows:

$$I(t) = i_1(t) + i_2(t) + i_3(t) + i_4(t) + \dots + i_n(t) \quad (3-3)$$

Theoretical analysis shows that when the capacitor is stored in constant energy:

1. The peak time of pulse current declines with the decrease of capacitor capacity.
2. The larger the L_0 , the smaller the peak, the greater the peak time.
3. The internal resistance of the armature, the internal resistance of the module and the track resistance all increase the decreasing speed of the pulse current.
4. The larger the inductance gradient, the greater the armature bore speed.

3.2. Kinematics Equations

The cross section diagram of the guideway and armature is shown in figure 4, regardless of the current skin effect, assuming that the current $I(t)$ in the guideway is evenly distributed, and the bulk current in the guideway is $J = I(t)/(hw)$. Where h is the height of the guideway, w is the width of the guideway, and s are the distance between the left and right guideways [7-9].

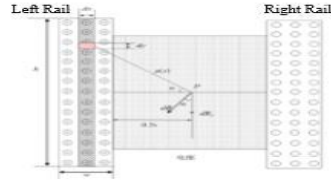


Figure 4. Schematic diagram of cross-section magnetic field analysis of rail and armature.

The average magnetic induction intensity in the armature is approximately equal to the magnetic induction intensity of the P point at the center of the armature. Due to the symmetry of the left and right rails, the P point magnetic induction intensity of the P point is obtained from the Pio-Savar law as follows:

$$B_y = 2 \frac{u_0}{4\pi} \int_{-0.5h}^{0.5h} \frac{I(t)}{whp(x)} \cos \cos \alpha dy dx$$

$$= \frac{u_0 I(t)}{\pi wh} \left(\frac{h}{2} \ln \frac{(2w+s)^2 + h^2}{s^2 + h^2} + w \tan^{-1} \frac{h}{s+2w} \right) \quad (3-4)$$

Then the ampere force on the armature is

$$F = B_y I(t) s = 1 / 2 L_r' I^2(t) \quad (3-5)$$

Of which:

$$L_r' = \frac{2u_0 s}{\pi wh} \left(\frac{h}{2} \ln \frac{(2w+s)^2 + h^2}{s^2 + h^2} + w \tan^{-1} \frac{h}{s+2w} \right) \quad (3-6)$$

The inductance gradient of the rail is determined by the structural parameters of the rail. combined with the distance between the guideway and the structural parameters of the track, the mathematical simulation model is established, and the variation curve of the inductance gradient is obtained, as showed in figure 5.

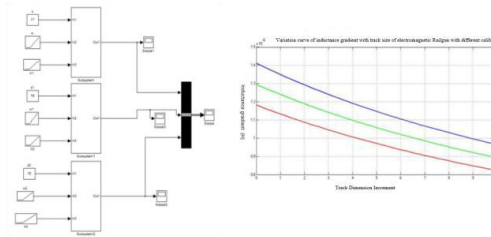


Figure 5. Inductance gradient simulation model and schematic diagram with track size.

Figure5 shows that the inductance gradient increases with the increase of the guide rail spacing and the inductance gradient decreases with the increase of the guide rail structure parameters.

In addition to the inductance gradient, the mass of the armature is also a key factor affecting the initial velocity of the muzzle.

$$v(t) = v_0 + \frac{L_r'}{2m} \int_0^t I^2(t) dt \quad (3-7)$$

$$x(t) = x_0 + v_0 t + \frac{L_r'}{2m} \int_0^t \int_0^t I^2(t) dt dt \quad (3-8)$$

$$R_r(t) = 2R'_r(x_0 + v_0 t + \frac{L'_r}{2m} \int_0^t \int_0^t I^2(t) dt dt) \quad (3-9)$$

$$L_r(t) = 2L'_r(x_0 + v_0 t + \frac{L'_r}{2m} \int_0^t \int_0^t I^2(t) dt dt) \quad (3-10)$$

$$e(t) = \frac{1}{2} L'_r I(t) (v_0 + \frac{L'_r}{2m} \int_0^t I^2(t) dt) \quad (3-11)$$

Where: m is the armature mass; v_0 is the initial velocity of the armature; x_0 is the filling position of the armature; $v(t)$ is the initial velocity of the armature; $x(t)$ is the displacement of the armature; $R_r(t)$ is the orbital resistance gradient; $e(t)$ is the armature induction EMF.

When the armature velocity is zero and the electromagnetic driving force is smaller than the armature sliding friction force, the armature and the track are static friction state, and the static friction force is equal to the armature driving force.

3.3. Launch efficiency

In the process of electromagnetic emission, the total energy of the system is constant according to the law of conservation of energy.

The system energy conversion efficiency is defined as the ratio of the kinetic energy obtained by the armature to the initial energy storage of the capacitor bank. Therefore, the emission efficiency of the electromagnetic rail gun can be expressed as:

$$\eta = \frac{W_{km}}{W_e} = \frac{\frac{1}{2} m_p v_m^2}{\frac{1}{2} C U^2} \quad (3-12)$$

W_{km} is the total kinetic energy of the armature; W_e is the initial energy storage of the module power supply; v_m is the outlet speed of the projectile, C and U are the capacitance and discharge voltage of the module power supply respectively.

4. Optimization and Test Verification of Rail Gun Parameters

4.1. Parameter Simulation Analysis

In order to facilitate the parameter optimization simulation analysis of the electromagnetic track gun launching system, the following assumptions are made:

The orbits of the electromagnetic rail gun are rigid bodies, forming circuits with the armature.

(2) there is adequate insulation between the track and the electromagnetic track shell, and there is no current loss.

The distance between orbits is fixed, the current distributes evenly along the section, and the direction of current density and the axis of symmetry constitute the right - hand spiral relation.

(4) the influence of air resistance and gravity on armature emission efficiency are not considered in the process of armature motion.

In the electromagnetic rail gun launch system, any change of parameters will affect the armature exit speed and launch efficiency. In order to obtain a larger outlet speed, the easiest way is to increase the capacitance and charging voltage of the capacitor bank.

Under the same energy storage level, the most effective way to improve the energy conversion

efficiency of the system is to optimize the structure parameters of the electromagnetic emission system, improve the emission efficiency of the system and increase the speed of the projectile outlet.

Under the condition of certain launching energy, the exit speed of the electromagnetic rail gun mainly depends on the action time of the current, the inductance gradient of the track, the current flow capacity of the armature and the quality of the armature. The action time of the current is determined by the length of the track, the inductance gradient is determined by the width and height of the track, and the current flow capacity of the armature is determined by the armature contact area, that is, the precipitating force. Therefore, taking the track length l , width W , height h , the mass m of the armature and the precipitating force F of the armature as variables, and taking the launch velocity v as the output, the functional expressions of the structural parameters and the launching velocity of the electromagnetic track gun are established, such as the formula. 4-1.

$$v = f(l, w, h, m, F) \quad (4-1)$$

By means of orthogonal simulation,⁹⁰ sets of electromagnetic emission data are obtained by circuit equation and motion equation simulation.

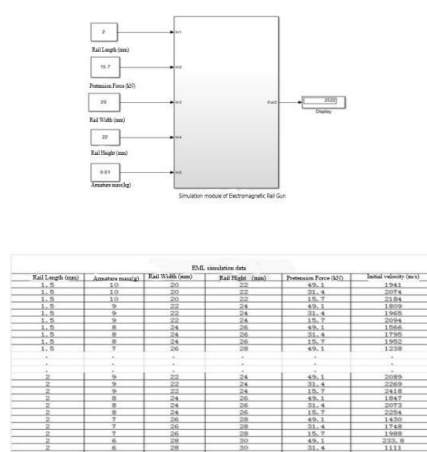


Figure 6. Simulation model and calculation diagram of electromagnetic rail gun.

In the process of electromagnetic launch test, the launch speed is affected not only by structural parameters, but also by air resistance, track state, contact area and other factors. Therefore, the mathematical simulation model of electromagnetic track gun needs to be constantly improved and optimized according to the test data in order to realize the accurate prediction of the structural parameters of electromagnetic track gun. In order to realize the feedback of the test data to the structural design parameters, a three-layer forward neural network is established by using the self-learning, adaptive and nonlinear characteristics of BP neural network, the structure of which is shown in figure 7.

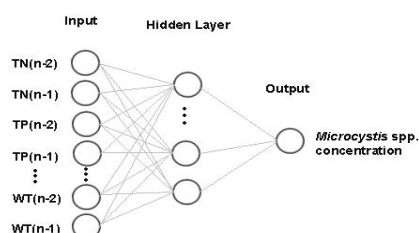


Figure 7. Neural Network Structure.

In this neural network, the structural parameters of the electromagnetic orbital gun are used as the input variables of the network model, and the firing speed is used as the output. The number of neurons in the input layer and the output layer is based on the empirical formula

$$s = \sqrt{0.43mm + 0.12n^2 + 2.54m + 0.77n + 0.35} + 0.51 \quad (4-2)$$

In the formula, s represents the number of neurons in the hidden layer, m represents the number of neurons in the input layer, and n represents the number of neurons in the output layer. Thus, the number of neurons in the hidden layer is 5. Each neuron is connected to the next layer of neurons, through which the neurons receive and transmit data signals in only one direction, from the input layer to the implied layer and then to the output layer. Partitioning force F is a variable, and the number of neurons in the output layer is 1 (Emission Velocity), and its structure is shown in figure 8.

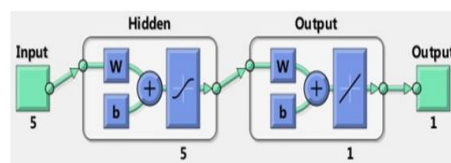


Figure 8. schematic diagram of BP neural network structure of electromagnetic rail gun.

The sample value range of the input variable is shown in table 1.

The 90 sets of electromagnetic rail simulation results are input into the neural network for repeated network training.

Table 1. Design Range of Electromagnetic Rail Gun Parameters.

Name	Rail Length	Rail Width	Rail Thickness	Armature mass	Pretension force
Scope	1.5m~2.0m	20mm~30mm	20mm~30mm	6g~10g	15.7kN~49.1kN

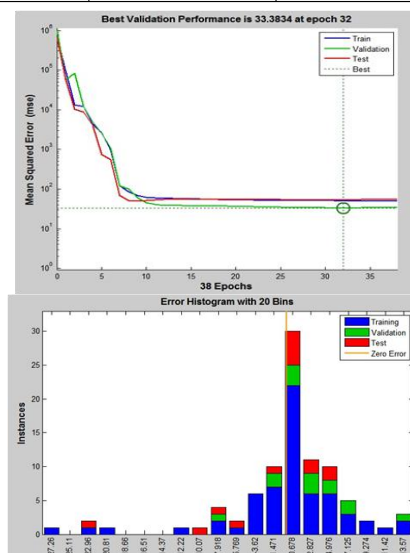


Figure 9. Schematic diagram of error result of simulation analysis of electromagnetic track gun neural network model.

The simulation results show that in the whole simulation model, the mean square error of the verification sample is more than 33.38 and 60% of the input sample, and the error between the verification samples and the test samples is less than 4.976.,BP neural network training results meet the

accuracy requirements.

The linear regression of input sample, validation sample and test sample is analyzed, the results are shown in figure 10.

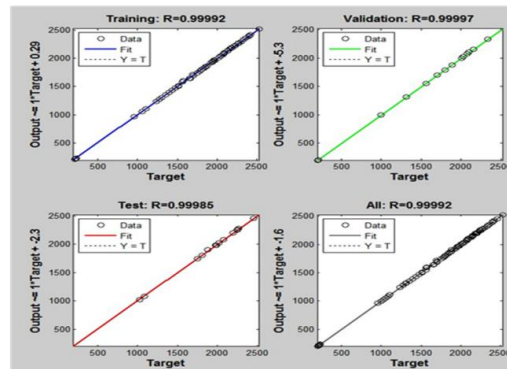


Figure 10. Linear regression results of electromagnetic rail gun parameter samples.

The linear regression coefficient of the whole neural network is 0.99992, which indicates that the input variables are positively correlated with the output variables, and the degree of interdependence is high, and the neural network model is accurate.

Under the condition of certain emission energy, according to the structural design and charge and discharge requirements of the electromagnetic track gun, the parameters related to the electromagnetic track gun are input according to the trained BP neural network model (table 2).

Table 2. Relevant parameters of electromagnetic rail gun structure design.

Name	Rail Length	Rail Width	Rail Thickness	Armature mass	Pretension force
Parameters	2m	22mm	25mm	10g	31.4kN

BP neural network calculation result is 2428.8 m / s.

In order to verify the simulation results of the neural network model, the firing speed, acceleration and current output curves of the electromagnetic track gun under the same parameters are obtained by using the mathematical model of the relevant parameters of the electromagnetic track gun, as shown in figure 11.

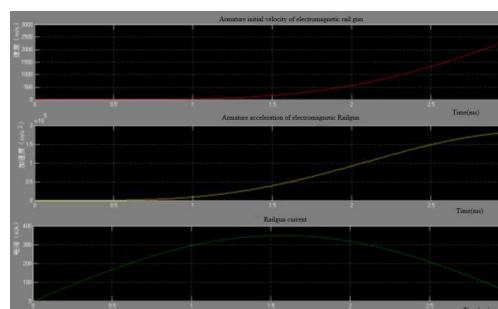


Figure 11. Simulation results of electromagnetic rail gun mathematical model under the same parameters.

From figure 11, it can be seen that the velocity of the electric pivot outlet of the electromagnetic track gun is 2358 m / s, and the error of the simulation results with the bp neural network model is 2.8%. the comparison results show that the bp neural network model can be used as the equivalent model of the numerical simulation model of the electromagnetic track gun.

4.2. Test validation and analysis of results

4.2.1. *Modeling and structural analysis of devices.* The electromagnetic emission test device is mainly composed of three parts: emitter tube, confluence feeding device and trestle.

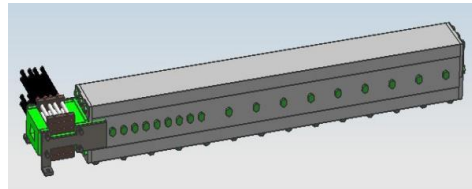


Figure 12. 3D model of electromagnetic emission test device.

In the process of electromagnetic emission test, the electromagnetic force changes with time and the displacement of armature. The inertia force is loaded into the structural design model by using the structural simulation software. In order to speed up the simulation process, the model is simplified, and the simulation results are shown in figure 13.

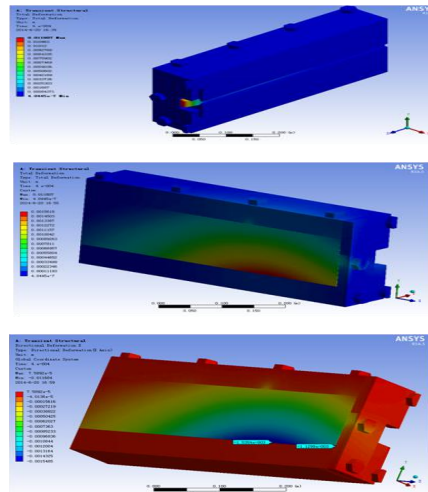


Figure 13. Simulation results of simplified model structure of test setup.

The simulation results show that in the process of electromagnetic emission, the left and right vertical plates of the test device have large force, easy to produce the shape and deformation of 1.53 mm. In order to increase the rigid strength of the structure, the left and right vertical plates are welded in the form of T-type lap joint, and the rigid strength of other parts of the device is increased to ensure that the test device meets the requirements of the index. the structure of the final test device is shown in figure 14.

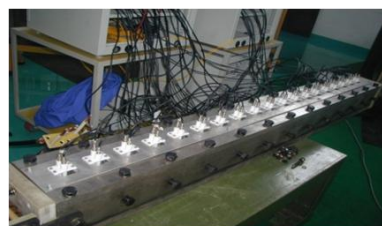


Figure 14. Schematic diagram of the launcher structure of the electromagnetic rail gun.

4.2.2. *Test verification of electromagnetic emission system.* The test pulse power supply adopts 1.2MJ power supply module, discharge voltage 6kV, and discharge according to the preset timing to ensure the

consistency of energy. The initial velocity of muzzle is measured by network target, and its structure is shown in figure 15.



Figure 15. Schematic diagram of network target test.

During the test, the rail material is chrome copper and the armature material is aluminum alloy, its related material parameters are shown in table 3.

Table 3. Key structural material parameters of electromagnetic rail gun system.

serial number	Rail Length	Armature mass	Rail Width	Rail Thickness	Pretension force	Initial velocity
1	2 m	10.2 g	20 mm	25 mm	15.7 kN	1981 m/s
2	2 m	10.8 g	20 mm	25 mm	15.7 kN	1892 m/s
3	2 m	9.8 g	20 mm	25 mm	15.7 kN	2106 m/s
4	2 m	10.3 g	20 mm	25 mm	31.4 kN	2028 m/s
5	2 m	10.4 g	20 mm	25 mm	31.4 kN	1864 m/s
6	2 m	10.8 g	20 mm	25 mm	31.4 kN	1821 m/s
7	2 m	10.1 g	20 mm	25 mm	31.4 kN	1796 m/s
8	2 m	10.2 g	20 mm	25 mm	49.1 kN	1753 m/s
9	2 m	10.0 g	20 mm	25 mm	49.1 kN	1715 m/s
10	2 m	10.5 g	20 mm	25 mm	49.1 kN	1682 m/s

Under the condition of constant caliber of electromagnetic emission test device, 10 emission tests were carried out using pulse power supply and net target, the relevant parameters are shown in table 4.

Table 4. Optimized electromagnetic rail gun launch results table.

Name	Density	Young's modulus	Tensile strength	Electrical conductivity
Chrome copper	8.9 g/mm ³	108 GPa	340 GPa	85%IACS
Aluminum alloy	2.7 g/mm ³	70 GPa	60 GPa	35%IACS

The parameters of 10 electromagnetic emission tests were taken as the training samples. The BP neural network trained by mathematical model is optimized again to adjust the number of neurons and threshold of its hidden layer, and the linear regression coefficient is 0.99926, and the result is shown in figure 16.

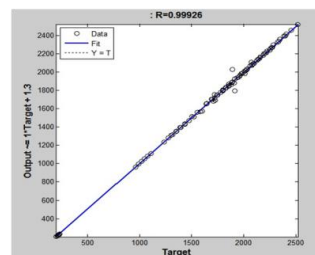


Figure 16. Optimized results of neural network linear regression after experimental data.

In order to analyze the performance of the optimized BP neural network, The experimental data,

unoptimized neural network output data and optimized neural network output data are compared respectively, the results are shown in figure 17.

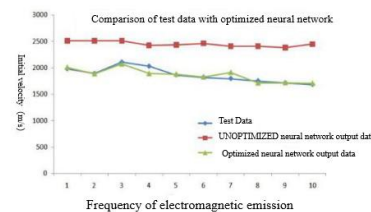


Figure 17. Schematic illustration of three different experimental data.

It can be seen from the data analysis in figure 17 that the output result of BP neural network which has not been optimized by electromagnetic orbit gun test data is about 25% different from the average true value of the test, which is because the influence of unpredictable factors such as contact area, air resistance, electrical conductivity, temperature and so on is not taken into account in the sample data of BP neural network before optimization, which leads to the simulation result being higher than the experimental value. The error is not more than 6.5%, so the optimized BP neural network model can use the relevant structure parameters of the electromagnetic rail gun to predict the initial speed of the gun opening of the electromagnetic launcher, improve the design level of the electromagnetic rail gun, and make effective use of the electromagnetic emission test data.

5. Concluding Remarks

Based on the principle of electromagnetic rail gun firing, a mathematical simulation model of electromagnetic emission is established. Based on the structure parameters of the orbit, the relative parameters of the armature and the pretightening force as input variables and the firing speed as output variables, a series of samples are obtained by simulation analysis, the BP neural network training samples are obtained, and the equivalent BP neural network model of the mathematical simulation model is obtained. The P neural network model is optimized. The experimental results show that the error of the BP neural network model optimized by the test data is 18.5% lower than that before the optimization. The structural parameters of the electromagnetic track gun provided by the model can be used as the basis for the design of the electromagnetic track gun and accelerate the design process of the electromagnetic track gun.

In order to further improve the simulation accuracy of the neural network model and improve the launching speed of the electromagnetic rail gun, the relevant parameters of the pulse power supply should be added to the electromagnetic track gun system to improve the robustness of the model.

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