Theoretical Analysis and Experimental Study on Rail Dynamic Load of Electromagnetic Launcher

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Abstract. In the course of electromagnetic launch, the rail deflection deformation seriously affects the service life and launch accuracy of the orbit. In order to reduce the deflection deformation in the process of orbital launch, based on the principle of electromagnetic emission, simplifying the orbit to Euler-Bernoulli beam, built moving load working conditions of the electromagnetic moving load model, using the electromagnetic launcher bore related structural parameters and material parameters for the rail electromagnetic theory analysis and calculation, the analysis results show that under the condition of the same peak current, rail the biggest position in midpoint deflection deformation; under different peak current ,the deflection of the midpoint of the rail increases non-linearly. The deflection of the rail can be effectively reduced by increasing the stiffness of the elastic support. According to the above theoretical analysis results, an electromagnetic launching device was developed. The experimental comparison results show that the deflection deformation is reduced by 42.86% and the critical launch velocity is increased by 6.86% with the increase of support stiffness.

1. Introduction
Electromagnetic rail cannon is a new conceptual movable emitting weapon with electric energy drive armature to ultra-high speed, has the advantages of high launching initial speed, high range of radius, strong radios, and the launch of flames, since it has been attached importance to various countries. I have experienced the principles research, experimental research, and it is currently developing the engineering prototype stage, and the application prospects are wide in the future military field.

The main structure of the electromagnetic orbital gun includes positive orbit, insulated support, and fastening components. During the electromagnetic transmission, the reverse pulse large current flows between the positive and negative rails, and the positive and negative rails produce interaction, and the size of the repulsive force changes with the magnitude of the current flow. The rail is subjected to electromagnetic repulsive and armature-to-orbit throughout the transmission process, and is in a vibration deformation state. When the speed of the armature reaches a threshold, resonance phenomenon is generated, causing deflection deformation of the rail, seriously affecting the orbit life and electromagnetic emission efficiency, hindering the further development of electromagnetic emission technology [1,2].

In this paper, according to principle of electromagnetic emission will be reduced to a simply supported beam with Euler-Bernoulli rail, build orbital dynamic equations of the moving load conditions, different pulse current conditions are analyzed and calculated by rail electromagnetic emission in the process of the deflection deformation, put forward to enhance the elastic support.
stiffness method reduces the deflection deformation orbit, and complete the design of electromagnetic launcher by electromagnetic emission test.

2. Electromagnetic Orbit Mobile Load Model Construction
The electromagnetic rail transmitter is mainly composed of two parallel orbitals and an armature located there between, and the rails and armature are packaged inside the electromagnetic emission device through the insulating material. During the electromagnetic transmission, the pulse current flows from one rail, and the armature flows to the other parallel orbit, forming a circuit. The electromagnetic transmitting device is internally formed in a powerful pulse magnetic field to produce powerful electromagnetic force. One side orbit is subjected to another side rail and the force of the armature between the two orbits, which moves as the armature movement toward the mouth of the transmitting device, when the armature leaves the emitting device part, the electromagnetic force disappears. During the entire transmission process, the load size of both sides is the same, and the direction is opposite, in order to simplify the calculation, only the single-side rail is theoretically loaded, so the single side rail is simplified into two end freely-based Euler-Bernoulli beams [3, 4]. It simplifies the model as shown in figure 1.

![Figure 1. Rail force model under mobile load.](image)

Under the moving load, the deflection deformation can be represented by the universal dynamic control equation for both free equation, and the specific equation is shown in the formula 1 of the formula [5, 6].

\[
 E \frac{bh^3}{12} \frac{d^4\omega(x,t)}{dx^4} + \rho bh \frac{d^2\omega(x,t)}{dx^2} + K\omega(x,t) = P(x, t) \quad (1)
\]

In formula 1, \(\omega(x,t)\) is the deflection variation of the rail; \(E\) is the elastic modulus of the rail material; \(b\) is the rail width; \(h\) is the rail thickness; \(K\) is an elastic support rigidity; \(P(x,t)\) is a movable load applied to the rail; \(x\) is the position of the armature moves on the rail; \(t\) represents time.

The formula 1 can be made to the Lapras series, and the deflection curve function \(\omega(x,t)\) of the rail position and time can be obtained, which is expressed as the formula (2).

\[
\begin{align*}
\omega(x,t) &= \frac{2}{L} \sum_{m=1}^{\infty} W(m,t) \sin\left(\frac{m\pi x}{L}\right) \\
W(m,t) &= \frac{p(x,t)v^2}{\rho bh L^2 \alpha^2} \left[ 1 + \left( \frac{\beta^2 \cos at - \alpha^2 \cos \beta t}{\alpha^2 - \beta^2} \right) \right] \\
\alpha &= \sqrt{\frac{K}{\rho bh} + \frac{Eh^2 (mn)^2}{12\rho L^4}} \\
\beta &= \frac{m\pi v}{L}
\end{align*}
\quad (2)
\]

In the formula (2), \(L\) represents the length of the rail; \(m\) is a half wave number; \(v\) is the sliding speed of the armature [7, 8].
Depending on the elastic mechanics, the rails are tended to symmetrically bend the speed, that is, when the critical speed, the structure response tends to be infinite, in order to avoid resonance phenomena, reduce the deflection deformation of the rail to avoid resonance phenomenon. It is necessary to derive the critical speed formula according to Timoshenko, determine the maximum speed of the armature emission [9, 10], the formula of the critical speed, as shown in the formula (3):

$$v_{cr}^2 = \frac{Ebh}{3kd^2}$$  \hspace{1cm} (3)

The movable load \( P(x, t) \) is mainly composed of two parts, a portion of the armature and the force; another portion is the repulsive force between the rail, and the \( P(x, t) \) can be represented as:

$$P(x, t) = F(t)\delta[x - S(t)] + q(t)[1 - H(x - S(t))]$$  \hspace{1cm} (4)

In the formula (4), \( S(t) \) is the distance from the tail of the armature distance transmitting device; \( \delta[x - l(t)] \) is a Dirac function; \( H(x - l(t)) \) is the Heaviside function [11, 12].

$$\begin{aligned}
q(t) &= \frac{\mu_0 l(t)^2}{2\pi d^2} \left[ 2(h + d) \tan^{-1}\left(\frac{h+d}{b}\right) - b \ln\left(\frac{b^2 + (h+d)^2}{b^2}\right) \right]
\end{aligned}$$

$$\begin{aligned}
F &= \frac{Qd^3E_0L^2}{12}\left[\frac{d}{v_0^2} + \frac{6}{v^2}\right]
Q &= 0.86 \cdot \frac{l^2}{\sigma_d}
J &= \frac{l(t)}{Ld}
\end{aligned}$$  \hspace{1cm} (5)

In the formula (5), \( \sigma_d \) is the armature conductivity, \( I(t) \) is an excitation current, \( \mu_0 \) is a vacuum magnetacid, \( d \) is between the two rails, \( L \) is the length of the rail, \( \phi, \psi, \varphi \) is an armature Linear expansion coefficient, thermal conduction coefficient, and surface heat exchange coefficient [13, 14].

In the formation of the 4-style and 5 types, the deflection deformation curve of the rail under the movement load can be obtained, and the theoretical expression is based on the theoretical expression, and the armature criminal can be obtained by MATLAB software. The deflection change curve of the rail under the speed.

3. Theoretical Analysis and Experimental Research

The Matlab software is used to prepare the theoretical analysis program with the corresponding parameters in table 1, table 2, and the change in the rail deflection under the action of the peak current 300kA pulse current is solved. The resulting comparison results are shown in figure 2.

| Table 1. Electromagnetic emission device rail structure parameters. |
|-----------------|--------|------|------|------|
| Structural parameters | L(mm) | b(mm) | h(mm) | d(mm) |
| Numerical value     | 1500   | 15   | 30   | 13   |

| Table 2. Electromagnetic emission device armature parameters. |
|-----------------|--------|--------|--------|--------|-----------------|--------|-----------------|--------|
| Material parameters | E (GPa) | \( \rho \) (kg/m³) | K (GPa) | \( \Phi \) (°C) | \( \Psi \) W/(m·°C) | \( \varphi \) W/(m·°C) | \( \sigma_d \) (\( \Omega \cdot m \))^\(-1\) |
| Numerical value    | 110    | 8900   | 110    | 1.65 \times 10^{-6} | 401     | 400             | 5.88 \times 10^{7} |
The analysis results of figure 2 show that under the same pulse current conditions, 1500 mm is the end point of the rail moving load, the deflection deformation is minimum, 0.05 mm; 750 mm position is the midpoint of the rail moving load, the maximum amount of deformation. The 52mm is 4 times the diameter position at 52 mm, and the deflection deformation is 0.15 mm, so the amount of deflection deformation in the rail must be effectively controlled.

The amount of deformation of the rail deflection is affected by the rail position; on the other hand, it is affected by the rail pulse current, that is, the effect of electromagnetic force. In terms of the characteristics of point deflection deformation in the rail, 100 kA, 200kA, and 300 kA of pulse current are used, respectively, and the results obtained are shown in figure 3.

The calculation results of in figure 3 show that before 1 ms, when the peak current of the midpoint of rail is 100 kA, 200kA, and 300 kA pulse current electromagnetic force, the deflection deformation is very small and tend to zero; After 1 ms, the electromagnetic force with the peak value of 200kA and 300kA pulse current acted on the midpoint of rail, resulting in increasing deflection amplitude variation, while the force of peak value of 100kA pulse current was basically 0 before 2ms, when the armature reaches the midpoint of rail at 1.75ms, 2ms and 2.4ms, the armature pressure generated by the three pulse currents and orbital repulsion force lead to the wave peak at the midpoint of rail, and the deformation is 0.31mm,0.24mm and 0.12mm, respectively. The rail midpoint deformation decreases form 1.75ms, 2ms and 2.4ms to the end of the electromagnetic launcher, the deflection of midpoint in
rail must be considered.

According to the above analysis, in order to reduce the amount of point deflection deformation in the rail, improve the electromagnetic emission speed, it is necessary to enhance the elastic support stiffness of the rail, and therefore, in the case of critical speed, the rail elastic support stiffness pair deflection and critical speed are analyzed. The result is shown in figures 4, 5.

![Figure 4. Variation curve of deflection with stiffness of elastic support.](image1)

![Figure 5. Curve of critical velocity changing with stiffness of elastic support.](image2)

The calculation results of figures 4 and 5 showed that as the ribroom elastic support rigidity increases, the amount of deformation of the rail deflection decreases, and the critical speed increases with an increase in elastic support stiffness. Therefore, the rail deflection deformation can be effectively reduced by increasing the elastic support stiffness.

According to the above analysis results and in combination with the relevant parameters in table 1 and table 2, the electromagnetic orbit launcher is designed. The device has the loading function of orbit elastic support, and its physical structure is show in figure 6.

![Figure 6. Physical electromagnetic orbit launcher.](image3)
In the process of electromagnetic launch test, pulse current with a peak current of 300kA is first provided to the electromagnetic rail launcher, and the waveform of the current is shown in figure 7.

![Diagram of 300kA pulse current waveform.](image)

**Figure 7.** Diagram of 300kA pulse current waveform.

At the same time, 3D laser vibrometer is used to measure the vibration deformation of the rail midpoint in the electromagnetic launch process, including the deformation of the rail midpoint in the electromagnetic launch process before the rigid support is loaded and the deformation of the rail midpoint in the electromagnetic launch process after the rigid support is loaded. The test results are shown in figures 8 and 9.

![Deformation of rail midpoint before loading of rigid support.](image)

**Figure 8.** Deformation of rail midpoint before loading of rigid support.

![The deformation of the rail midpoint after the rigid support is loaded.](image)

**Figure 9.** The deformation of the rail midpoint after the rigid support is loaded.

In the test results in figure 8, when no rigid support is loaded, the maximum deformation at the
midpoint of the rail is 0.35mm, and the error from the theoretical calculation is 0.04mm. After the rigid support is loaded in figure 9, the deformation at the midpoint of the rail is 0.2mm, and the maximum deformation of the rail is reduced by 42.86%. The comparison results show that under the condition of 300kA current, the enhanced stiffness support can reduce the deflection deformation of the rail.

In order to verify the deflection deformation before and after loading the rigid support at the rail midpoint under the condition of small current, a pulse current of 100kA was selected to carry out the emission test. The current waveform is shown in figure 10.

![Figure 10. Diagram of 100kA pulse current waveform.](image)

Armature emission test was carried out under the current state of 100kA, and the test results are shown in figures 11, 12.

![Figure 11. Deformation of rail midpoint before loading of rigid support.](image)

![Figure 12. The deformation of the rail midpoint after the rigid support is loaded.](image)
In figure 11, when no rigid support is loaded, the maximum deformation at the midpoint of the rail is 0.15mm, and the error from the theoretical calculation is 0.03mm. After the rigid support is loaded in figure 12, the deformation at the midpoint of the rail is 0.075mm, and the maximum deformation of the rail is reduced by 50%. The comparison results show that at the current of 100kA, increasing the stiffness support can also reduce the deflection deformation of the rail.

With the loading of the rigid support, the critical velocity of the transmitter increases from 1440m/s to 1500m/s under the condition of pulse current with the peak value of 300kA, which increases by 8.6%, and the transmission efficiency is greatly improved.

4. Conclusion

In order to enhance the dynamic load characteristics of the electromagnetic device rails, reduce the deflection deformation of electromagnetic launcher rail, improve the efficiency of emission, rail electromagnetic launcher, this paper constructs the theoretical model, the deformation of rail dynamic load conditions are analyzed and calculated by the deformation, put forward by increasing the rigid support method reduces the deflection deformation and improve the efficiency of emission, and is verified by electromagnetic emission test, the following conclusions:

1) In the course of electromagnetic launch, the deformation of midpoint deflection is the largest near the critical velocity.

2) The enhanced stiffness support of electromagnetic launcher can reduce the deflection of rail by more than 40% and increase the critical velocity by more than 5%, so that the overall performance of the launcher can be improved. Therefore, the design of rail rigid support structure should be emphasized in the design of electromagnetic launcher.

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