Research Article

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Analysis of electromagnetic characteristics of the proposed composite four-rail electromagnetic launcher

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Abstract: In the existing composite four-rail electromagnetic launcher (CFREL), the armature and rail contact surface produces significant heat and bears considerable wear, thereby reducing the potential amount of electromagnetic thrust to be generated. To eliminate the damage caused by the thermal effect of the rail contact surface and to meet the electromagnetic thrust demand of the load, a CFREL is proposed. The proposed CFREL model is constructed, and the launcher’s electromagnetic characteristics are simulated and compared using the finite element method. The current density, distribution of magnetic flux density, and electromagnetic thrust characteristics are analysed. The results showed that the proposed CFREL reduced the maximum current density of the contact surface and effectively eliminated the current concentration of the armature and rail contact surfaces. Effective magnetic field shielding is realised with a larger range, which can better meet the requirements of the intelligent load’s magnetic field environment and provide stronger electromagnetic thrust for the load, hence solving the problem of insufficient thrust.

Keywords: electromagnetic launch, quadrupole magnetic field, electromagnetic characteristic, electromagnetic thrust

1 Introduction

Electromagnetic launch technology is a new weapon-launching technology that uses the electromagnetic force generated by a high-pulse current to drive a load at high speed within a very short time [1–3]. Its advantages are controllable thrust, good concealment, sustainable operation, and broad development prospects in military applications [4–7]. With the development of “intelligent” loads, many high-precision electronic devices depend heavily on the electromagnetic environment. At the same time, the armature and rail contact surface is prone to thermal damage and mechanical wear because of the current concentration during the launching process. These challenges the structural design of the electromagnetic rail launcher [8–13]. To effectively protect the high-precision electronic components in the load, Gutierrez et al. [14] suggested applying a quadrupole magnetic field to the coil launcher. On this basis, Yang et al. [15,16] proposed using a four-rail electromagnetic launcher (FREL). The magnetic fields produced by the rail of the FREL are offset from each other at the armature centre, which ensures magnetic shielding at a specific position and solves the shielding problems.

However, the electromagnetic shielding of the FREL at the armature centre is achieved at the cost of weakening the electromagnetic thrust, with persistent thermal damage and mechanical wear at the contact between the armature and rail. To enhance the electromagnetic thrust of the FREL, while maintaining adequate electromagnetic shielding effects and eliminating the mechanical wear of the contact surface to a certain extent, the application of a composite material rail is considered a potential solution. Additionally, to meet the load’s electromagnetic thrust demand, a proposed rail system should be employed.

Relevant research has been conducted on this topic [17–21]. Yin [22] developed a calculation model in terms of the dynamic contact pressure using the Ampere law and the electromagnetic properties of the composite
armature. Xie et al. [23] focused on a systematic summary of the development of electromagnetic launcher rail materials, elaborated on the performance of the relevant materials, and pointed out that the composite rail materials have broad development prospects. Tian et al. [24] also explored the distribution of current, temperature, and stress in the coupling field of a composite electromagnetic rail under launching conditions. However, the above research is based on the standard two-rail electromagnetic launcher, with limited research on the enhanced composite four-rail electromagnetic launcher’s (ECFREL) electromagnetic characteristics.

Based on the literature review and knowledge gap, this article presents an investigation on both the standard composite (CFREL) and the proposed ECFREL, mainly focusing on the electromagnetic characteristics of the launcher and comparison and analysis of the current density distribution, magnetic field distribution, and armature stresses. The feasibility and performance superiority of the ECFREL are verified, providing a theoretical reference for the design and application of quadrupole electromagnetic launchers.

2 Physical model and simulation conditions

2.1 Modelling of the proposed ECFREL and the standard CFREL

The models of the ECFREL and CFREL are shown in Figure 1.

The main rail is used to carry the armature, while the additional rail is used to enhance the magnetic field. Due to its good electrical and thermal conductivity, copper is used as the matrix material of the main rail to ensure the current carrying capacity and the magnetic field environment required for launch. With its good rigidity and ablation resistance, steel can improve the wear resistance of the main rail as the reinforcement material. The combination of these two materials can give full play to their advantages. To further ensure good electromagnetic thrust of the launcher, copper is selected as the additional rail material. The main and additional rails are symmetrically installed around the armature, which is conducive to the launcher’s structural stability.

The launcher uses a power supply set, where the current directions of the adjacent main and additional rails are opposite to each other, while the current directions of the relative main and additional rails are the same. The current flows from the copper rail’s end face of the composite rail, passes through the steel rail, flows through the armature, and then flows out from the adjacent rail. The rail current generates a quadrupole magnetic field in the launch region, which is orthogonal to the current flowing through the armature and drives the armature to move in the +Z direction. The launcher forms a weak magnetic field at the armature centre to achieve electromagnetic shielding.

The structure of the quadrupole armature is shown in Figure 2:

The armature adopted a hollow design, which leaves loading space for ammunition, saves material, reduces quality, and improves launch efficiency. The long armature tail can ensure good contact between the armature and rail; the four drainage arcs of the armature can guide and concentrate the current to improve the current utilization to achieve a larger electromagnetic thrust.
The direction of the magnetic field, the current of the proposed ECFREL are shown in Figure 3. It can be seen that the current is mainly concentrated in the four stages of the drainage arc, and the setting of the drainage arc has a certain rationality; due to the structural characteristics of the launcher, the magnetic field generated by the rail current cancels out each other in the middle of the launch area, forming a hollow magnetic field, weakening the strong magnetic interference, and can very well meet the requirements of the intelligent load on the magnetic field environment.

### 2.2 Material parameter setting and simulation conditions

In the simulation experiment of the electromagnetic launcher, the electromagnetic characteristics of the main and additional rails are qualitatively simulated by comprehensively considering the flow capacity and mechanical strength of the armature and rail. The parameters of the rail and armature are shown in Table 1. The conductivities of aluminium, steel, and copper are $3.8 \times 10^7$, $1.0 \times 10^7$, and $5.8 \times 10^7$ S/m, respectively.

Since the armature movement out of the chamber under electromagnetic thrust is a complex transient acceleration process within milliseconds, the eddy current solver is employed to solve the problem. When the current frequency reaches a specific value, the current skin effect is simulated. In the simulation, the solid current path is fixed; the current frequency is 2 kHz, and the current amplitude is 500 kA. Due to rapid changes in current over short periods, an induced current is generated, that is, the nonelectrified part will produce an eddy current effect, while the electrified part produces a current skin effect. Therefore, the skin effect of the current can be considered by fixing the “eddy effect.” To improve the accuracy of the simulation results, an adaptive mesh generation technology is adopted in this section, and the related calculation procedure is shown in Figure 4.

The maximum number of iteration steps is 20, the minimum energy error is 0.1%, and the incremental mesh ratio is 35%. If the maximum number of steps or energy error is less than 0.1%, the simulation is said to have converged and is terminated; otherwise, the number of grids will be increased by 35% based on the previous step until the simulation is completed. Because the

| Component  | Material | Length (mm) | Width (mm) | Height (mm) |
|------------|----------|-------------|------------|-------------|
| Additional rail | Copper  | 400         | 20         | 40          |
| Main rail   | Copper  | 400         | 15         | 40          |
|             | Steel   | 400         | 5          | 40          |
| Armature    | Aluminium | 80         | 80         | 40          |
relative permeability of the copper rail and armature material is close to that of air, the phenomenon of magnetic flux leakage should be considered. Therefore, the air around the armature and rail should be modelled. The vacuum region is fixed at 300% to improve the calculation efficiency and ensure accurate solution results.

Figure 5 is the meshing situation after using the technical principle of the adaptive grid section. After the model is meshed, a mesh quality check is required, and when the mesh quality reaches 0.7, the mesh quality can be considered to be up to standard. After using the above dimensions to divide the mesh, the mesh quality of the armature is 0.88, and the mesh quality of the rail is 0.90, indicating that the meshing is better and can meet the simulation requirements.

In this article, the finite element method is used to simulate the CFREL and ECFREL, and the current density and magnetic field distribution are analysed and compared. The finite element method, also known as the matrix approximation method, is based on the variational principle and the weighted residual method. The core idea is “numerical approximation” and “discrete,” which simplifies the solution domain of the complex system problem into a large number of limited interconnected non-overlap subdomains, then derives the approximation of the whole system by solving the subdomain and then uses the principle of variable division or the weighted margin method to derive the approximation of the whole system so that a continuous infinite degree of freedom problem becomes a discrete finite degree of freedom problem. Using this method, the high-precision approximate calculation of the simulation model in this article can be realised.

3 Analysis of simulation result

3.1 Analysis of current density distribution

The distribution of the current density will directly affect the distribution of the magnetic field, while the intensity and position of the current density will affect the generation and accumulation of heat. The more concentrated the current is, the higher the corresponding heat produced, resulting in material softening or thermal damage caused by heat accumulation. The thermal damage of the armature will directly affect the launch efficiency of the CFREL, and the thermal damage of the rail will directly affect the service life of the CFREL. Therefore, studying the current density distribution of the armature and rail of the proposed ECFREL and the standard CFREL is necessary.

Figure 6 is a diagram of the rail current density distribution of the CFREL and ECFREL.

Figure 6(a)–(d) shows that the current density distributions of the standard rail and proposed rail are different. Under the same current conditions, the maximum current density of the proposed ECFREL is up to $1.62 \times 10^{10}$ A/m$^2$, while that of the standard CFREL rail is up to $1.17 \times 10^{10}$ A/m$^2$.

From the position of the current distribution, the difference between them is also apparent. Because the main
rail is made of two materials and the conductivity of copper is much higher than that of steel, the current is mainly distributed on the copper rail. The current in the CFREL is distributed primarily on the thin surface layer of the rail and rarely in the middle region. The current density on the four edges of the rail is large, with the largest value recorded on the inner edge of the rail, which is due to the current skin and proximity effects. Opposite current directions are observed in the two adjacent rails, which satisfies the condition of the current proximity effect (closeness to each other), resulting in a more concentrated distribution of current on the inner edge.

The current distribution of the proposed ECFREL is similar to that of the standard CFREL. The main difference here is that the current is distributed more outside the additional rail and inside the main rail. Nevertheless, there is no apparent current concentration in the inner corner of the copper-based rail. The current is highly concentrated at the armature-rail contact, causing a large current density at this position. There is little current flowing through the rest of the steel rail. The current of the proposed main rail is mainly distributed on the inner side, while the current of the additional rail is mainly distributed on the outer edge. The current in the inner side of the additional rail corresponding to the current passage section of the main rail is less distributed, which is mainly affected by the current skin and proximity effects. In the unpassed current section of the main rail, the current distribution appeared on the inside of the additional rail, which indicates that the skin tending effect of the current and the neighbouring effect significantly affects the current distribution.

It can be seen from the above analysis that the current distribution on the contact surface of the armature and rail is also uneven. To intuitively show the current distribution on the contact surface, the armature and contact surface are selected for further simulation analysis, with the results shown in Figure 7.

Due to the structural design of the quadrupole armature, the current is mainly distributed on the four drainage arcs, which shows the importance of drainage arc setting in conducting current. Additionally, there is a higher current distribution on the inner edge of the sliding contact surface, which is determined by the shortest path of the current. Figure 7(b) shows that due to the proximity effect of the current, the surrounding current of the contact surface is relatively more concentrated, with almost no current distribution in the middle of the contact surface. From the tail of the armature arm, the zero current region of the contact surface is seen as an “inverted platform,” with the maximum current density mainly concentrated in the head and tail of the contact surface, which is related to the conduction path of the current.

In terms of current, the maximum current density of the standard armature is up to $2.19 \times 10^{10} \text{A/m}^2$, while that of the proposed armature is only $1.97 \times 10^{10} \text{A/m}^2$, a 10.1% reduction. At the same time, the maximum current density on the contact surface of the standard type is 1.19 times higher than that of the ECFREL. This shows that the proposed ECFREL can reduce the maximum current density and improve the current distribution on the contact surface.
density of the armature and contact surface, improve the current distribution on the contact surface, and effectively eliminate the thermal damage caused by the current concentration.

For a quantitative analysis of the current distribution of the contact surface, paths 1–3 are selected to extract the current value of each path, as shown in Figure 8.

Figure 9 shows that the current distribution changes on each path are consistent. The current density change on path 1 of the standard CFREL is largest at the armature head but decreases rapidly from 0–4 mm and then maintains a slower decline up to 5 mm away from the tail of

Figure 7: Current distribution in the armature. (a) Current density of CFREL, (b) current in contact surface of CFREL, (c) current density of ECFREL, and (d) current in contact surface of ECFREL.

Figure 8: Map of the location of three paths of the armature.

Figure 9: Current distribution on three paths.
the armature and then quickly rises. This phenomenon can be closely related to the conductivity of the materials. The distribution results of paths 2 and 3 are consistent with that of path 1. However, a near-zero current density is observed in the middle of paths 2 and 3, that is, no current distribution occurred. This shows that the current on the contact surface is mainly distributed in the limited area on both sides of the surface.

According to the above analysis, due to skin tending effects, the current in the rail is mainly distributed along the guide rail’s surface; hence, the cross-sectional current in the rail is further explored by selecting the path shown in Figure 10.

Figure 11 shows the current distribution on the cross-section of the rail. Using the proposed ECFREL as an example, three peaks of currents A, B, and C, with respective current densities $3.23 \times 10^9$, $3.01 \times 10^9$, and $9.03 \times 10^9$ A/m$^2$, are observed on the rail path 4. This depicts that the current is concentrated at the edges and corners. Here the highest value is obtained at point C, indicating that the current is more concentrated on the inner edge of the main rail, with minimal distributions on the outer edge of the rail, which is consistent with our previous analysis. The current at the same position of the standard CFREL is considerably different from the proposed one, where current densities at A, B, and C are found to be $4.19 \times 10^9$, $4.93 \times 10^9$, and $3.44 \times 10^9$ A/m$^2$, respectively. It is self-evident that the current density C is significantly less than that of the ECFREL, which indicates that the current of the standard CFREL is more concentrated outside of the rail.

On path 5, three peaks $A'$, $B'$, and $C'$ are also observed, with respective current densities of $6.67 \times 10^9$, $5.08 \times 10^9$, and $3.34 \times 10^9$ A/m$^2$, showing that the current is mainly distributed in the outer edges of the additional rail. The current density of the proposed main rail A and B is almost 0, indicating that it is significantly affected by the current proximity effect.

The current density of the additional rail is higher in the middle of $A'$ and $B'$. Compared with the current density of each point at the corresponding position of the main rail, there is a strong current distribution outside the additional rail and inside the main rail.

### 3.2 Analysis of the magnetic field distribution

As one of the factors that affect the electromagnetic thrust, the magnetic field distribution is closely related to the distribution of current. Based on the current density analysis, the magnetic flux density of the two launchers is analysed. The results are shown in Figure 12.

The magnetic field distribution has a distinct characteristic: the magnetic field concentration appears at the copper–steel junction, and the magnetic flux density on the steel rail is relatively large. Due to the influence of the current distribution, the external rail surface of the standard CFREL has a stronger magnetic field distribution. At the same time, the magnetic field of the proposed ECFREL is mainly distributed at the outer edge of the additional rail, with a relatively small magnetic flux density on the outer surface of the main rail.

The cross-sections shown in Figure 13 are selected to analyse the magnetic field inside the launcher.

The magnetic fields generated by the rail current cancelled each other in the middle of the launching area, forming a hollow magnetic field that weakened the strong
magnetic interference, perfectly meeting the requirements of the magnetic field environment of intelligent ammunitions. There is a strong magnetic field at the bottom of both the armatures related to the current distribution. A strong magnetic field is also observed on both sides of the rail. Comparing the magnetic field of the proposed ECFREL and the standard CFREL, it is found that the magnetic induction intensity of the ECFREL is up to 24.23 T, while that of the CFREL is only 16.92 T. This indicates that the proposed ECFREL has a stronger magnetic flux density and can provide a larger electromagnetic thrust.

To intuitively analyse the magnetic field near the armature, the magnetic flux density of the front and rear end faces of the armature is simulated. Figure 14 represents the cloud diagram of the magnetic flux density distribution of the front and rear end faces of the armature.

Analysis of the magnetic field around the standard end surface of the armature showed that the magnetic field distribution of the surface is symmetric. The zero magnetic field region is visible in the middle region of the armature, which is the characteristic of the quadrupole magnetic field and can effectively achieve the electromagnetic shielding of that specific region of the armature. The magnetic flux density of the front end is 20.6 T, and the rear end is 21.5 T, depicting that the magnetic flux density of the rear end of the armature is greater than the front end. The maximum value of the magnetic flux density of the rear end of the armature is located at the armature drainage arc, which shows that the design of the drainage arc is feasible. The electromagnetic thrust is generated orthogonal to the current and magnetic field, converging at the armature drainage arcs to improve the launch efficiency. The magnetic field distribution at the end face of
the proposed armature is similar to that of the standard armature; however, the magnetic flux density at the front end of the proposed armature reaches 30.3 T, while at the rear end, the face reaches 13.9 T. At the same time, there is a strong magnetic field distribution on the steel rail.

To analyse the magnetic flux density at different cross-section positions and explore the magnetic field distribution characteristics, four paths (paths 6–9) are set, as shown by the red line in Figure 15. Among them, path 6 is 40 mm away from the bottom of the armature and parallel to the bottom of the armature; paths 7 and 8 are at the bottom and head of the armature, respectively; and path 9 is 40 mm away from the armature and parallel to the armature head. The position relationship of the four paths is shown in Figure 15. The four routes of the standard CFREL and the proposed ECFREL are simulated. The results are shown in Figure 16.

Figure 14: Magnetic field distribution of armature. (a) Front end of standard armature, (b) rear end of standard armature, (c) front end of proposed armature, and (d) rear end of proposed armature.

Figure 15: Map of the location of four paths. (a) Four paths of the standard CFREL and (b) four paths of the proposed ECFREL.
Figure 16(a) shows that the magnetic field distributions of the CFREL and ECFREL on path 6 are similar. Using the standard CFREL as an example, the current is mainly distributed outside the rail and is affected by the current skin effect. The larger the current density, the stronger the space-excited magnetic field; hence, the stronger the magnetic field outside the rail. From the outside to the inside, the current density is minimal, and the magnetic field decreases rapidly. However, there is almost no current distribution in the middle of the rail; hence, the magnetic flux density at this position is infinitesimal.

There is a significant change at 40 mm (the junction of the copper rail and steel rail), with a value of 8.2 T. In the launch region, the magnetic field decreased to 0 T, which is determined by the structural characteristics of the CFREL. The magnetic fields excited by the current cancelled each other in the launch region, forming a weak magnetic region. The magnetic field distribution of the proposed ECFREL is similar to that of the standard CFREL. The only difference is that the magnetic flux density between the main rail and the additional rail of the ECFREL is 0 T. This can be attributed to the near-zero current distribution and the lack of excitation of the space magnetic field in this region.

Intelligent loads are mainly installed in the front sides of the armature, namely, the path 8 positions. If the magnetic field is strong, it will interfere with the electronic equipment in the load and affect its performance, requiring a high magnetic field environment. However, the proposed ECFREL can adequately meet the launch demand owing to the following. In path 8, the magnetic flux density of the ECFREL is significantly smaller than that of the CFREL, with maximum values of 8.91 T and 15.94 T, respectively. Hence, the magnetic field interference on the intelligent load is smaller for the proposed ECFREL. Considering the shielding range of the magnetic field, the path range of the ECFREL is 45 mm and 125 mm when the magnetic flux density is 0–4 T in the launch area, while that of the standard CFREL with the same magnetic flux density is 75 mm and 108 mm. The magnetic shielding range of the proposed ECFREL is 2.42 times that of the standard CFREL.

Figure 16(d) shows that the magnetic flux density 40 mm away from the front-end face of the armature is small, with little difference between the ECFREL and the CFREL in the launch area. The maximum magnetic flux density is only 4.52 T. However, the magnetic flux density outside the additional rail of the ECFREL is still high because there is no current in the second half of the

Figure 16: Magnetic field of four paths. (a) Magnetic field of path 6, (b) magnetic field of path 7, (c) magnetic field of path 8, and (d) magnetic field of path 9.
main rail, which is only affected by the skin effect. From the magnetic flux density inside and outside the additional rail, it can be seen that the current is mainly distributed outside the additional rail.

3.3 Analysis of the electromagnetic force

During the operation of the CFREL, the current on the armature interacts spatially with the orthogonal magnetic field generated by the rail to produce an electromagnetic force. Part of the electromagnetic force is used to drive the armature at high speed, called electromagnetic thrust. The other part is used to provide good electromagnetic contact between the armature and rail. The electromagnetic force plays an essential role in armature motion and contact; hence, it is necessary to simulate and analyse it.

Figures 17 and 18 show that the electromagnetic force of the standard CFREL and the proposed ECFREL, respectively. Affected by the current and magnetic field distribution, there is a strong concentration around the tail of the electromagnetic armature of both the launchers; in addition, there is a strong electromagnetic force at the copper–steel junction of the main rail and the outside of the additional rail of the proposed ECFREL.

Table 2 shows the electromagnetic force on the two armatures.

| Armature        | $F_x$ (kN) | $F_y$ (kN) | $F_z$ (kN) | Mag $F$ (kN) |
|-----------------|------------|------------|------------|--------------|
| Proposed ECFREL | 0.953      | 1.568      | 89.465     | 89.484       |
| Standard CFREL  | 1.032      | 2.562      | 40.044     | 40.139       |

Table 2 shows that the armature forces of the proposed ECFREL and the standard CFREL are quite different. The electromagnetic thrust of the standard armature is 40.044 kN and that of the proposed armature is 89.465 kN, 123.42% higher than that of the standard armature. This indicates that the electromagnetic thrust of the device is significantly improved by adding the additional rail to meet the needed launching requirements. Compared to the forces in the $Y$ and $Z$ directions, the standard armature yielded a more significant force that can easily cause structural deformation, reduced firing accuracy of the launcher, and in some cases, severe damage after several firings. The electromagnetic force of the proposed armature in the $Y$ and $Z$ directions is significantly smaller than that of the standard armature; hence, the proposed ECFREL has better structural stability.
4 Conclusion

In this article, the electromagnetic characteristics of a proposed composite FREL (ECFREL) and a composite four-rail electromagnetic launcher (CFREL) are simulated and analysed with a summary of the results below:

1. ECFREL reduced the maximum current density of the armature and rail contact surface, improved the contact condition, and significantly reduced the thermal ablation of the contact surface caused by the current concentration. At the same time, the steel rail increased the wear resistance and stiffness of the rail and prolonged the armature and rail service life.

2. The ECFREL achieved self-shielding of the magnetic field at a specific location, with a higher shielding range than that of the CFREL, thereby meeting the requirements of an intelligent load magnetic field environment.

3. The ECFREL provided a larger electromagnetic thrust, thus producing a higher exit speed, to meet the exit speed requirements of an intelligent load. At the same time, the force of the armature is more concentrated, which is conducive to the stability of the structure.

4. Due to the strategy adopted in adding the additional external rail to enhance the electromagnetic thrust, the volume of the launcher is increased, necessitating a larger space. Hence, as a further study, space optimisation can be considered to fully explore the advantages of the proposed ECFREL.

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Author contributions: Li Tengda specifically carried out the simulation design and paper writing, Feng Gang mainly provided the ideas, and Liu Shaowei was mainly responsible for the result verification.

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