Simulation analysis of asynchronous induction type coil gun armature structure parameters

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Abstract. In this paper, the asynchronous induction coil gun is selected as the object of study, and its working principle is firstly briefly introduced, then the mathematical model is established by using the knowledge of electromagnetism, and then the MAXWELL component of ANSYS analysis software is used to simulate the velocity change curve of the projectile in the time domain under different conditions by combining static analysis and transient analysis, which reveals the relationship between the armature structural parameters such as armature material, armature axial length, armature position, armature inner diameter and armature outer diameter and projectile end velocity is revealed, and the influence of several structural parameters on the acceleration performance of coil gun launcher is summarized and analyzed, and the optimized design principles of armature are summarized according to the obtained conclusions to provide theoretical references for practical applications.

1. Introduction
The armature is a key component of the coil gun for energy conversion, and the structure of the armature has a significant impact on the acceleration performance of the coil gun. Due to the presence of skin effect and end effect in the magnetic field, the armature tail usually generates large induced eddy currents and acceleration forces, which cause temperature rise and deformation. Improving the armature structure parameters can help to improve the acceleration performance of the coil gun.

2. Principle Introduction
Coil gun, also known as "coaxial launchers" and "traveling wave launchers" in the early stages of research, use a moving magnetic field (i.e., magnetic traveling waves) generated by alternating or pulsed currents to drive a magnetic projectile or a coil with a emitter. The coil gun is similar in nature to a linear motor and operates by using the interaction between the magnetic field generated by the coupled magnetic field between the drive coil and the projectile to accelerate the projectile.

3. Mathematical model
Since a multi-stage coil-type electromagnetic launcher is difficult to implement in control theory, in order to facilitate the subsequent simulation, the mathematical model described in the previous section is simplified by studying only the single-stage coil and selecting a few parameters that have a direct effect on the projectile acceleration for analysis.

The first is the projectile force, which can be simplified for a point on the projectile in a single-stage coil as:

$$F_0 = CB I_p$$ (1)
Where \( C \) denotes the perimeter of the projectile, \( B \) denotes the effective value of the traveling magnetic field generated by the drive coil, and \( I_p \) denotes the induced current (eddy current) at that point on the projectile armature. Since \( I_p \) is a function of the axial length of the projectile armature versus time, the force at that point is integrated along the projectile axis to obtain the instantaneous force on the entire projectile:

\[
F = \int_0^l F_0 dl
\]

The collation yielded:

\[
F = \int_0^l CBIdl
\]  

(2)

If this drive coil is large enough so that the induced currents at each point on the projectile armature are equal, the instantaneous force on the projectile can be approximated as:

\[
F = CBIP_l
\]

(3)

Similarly, according to Newton's second law, the expression for the instantaneous acceleration of the projectile can be obtained as:

\[
a = \frac{CBIP_l}{M_p}
\]

(4)

Assuming that the initial velocity of the projectile is zero, the final velocity of the projectile is known from kinematic knowledge to be:

\[
v_f = \int_0^t \frac{CBIP_l}{M_p} dt
\]

(5)

Through Equation (6), it is not difficult to conjecture that the parametric variables of the projectile end velocity are the armature inner diameter, the armature outer diameter and the armature axial length, which need to be selected as variables for the projectile velocity simulation during the subsequent simulation to verify the accuracy of the conjecture.

4. Modeling and Analysis

4.1. Simulation model

4.1.1. Geometric model

MAXWELL 3D is used to build a 3D analysis model, and the solution type is set to static magnetic field solution. The model is shown in Figure.1, which consists of three regions, namely, the projectile coil region (coil casing outside the projectile body), the drive coil region (the coil can be considered as a uniform material) and the air gap region (free space). The inner diameter of the armature is 10 mm, the outer diameter is 30 mm, and the axial length is 60 mm; the inner diameter of the drive coil is 50 mm, the outer diameter is 80 mm, and the axial length is 50 mm.

To simplify the analysis, the three-dimensional model of the coil-type electromagnetic emitter is equated to the corresponding two-dimensional model for analysis. The simplified model is shown in Figure.1. The inner diameter of the armature is 10 mm, the outer diameter is 30 mm, and the axial length is 60 mm; the inner diameter of the drive coil is 50 mm, the outer diameter is 80 mm, and the axial length is 50 mm.
4.1.2. Driver circuit setting

In order to achieve the purpose of the study, the capacitive excitation is used in the two-dimensional transient model. The excitation circuit is shown in Figure.2, where the internal resistance of the drive coil is 0.09 ohm, the inductance is 19 $\mu$H, the initial voltage of the excitation capacitor is 1 KV, the capacitance value is 1800 $\mu$F, and the number of turns of the coil is 30.

4.2. Simulation Analysis

According to the previous theoretical analysis, it is known that the structural parameters of the armature (including the material of the armature, the shape of the armature, the axial length of the armature, the inner diameter of the armature, the outer diameter of the armature, etc.) have a very close relationship with the acceleration of the coil-type electromagnetic transmitter, so in this paper, different sizes of structural parameter variables are selected for the simulation analysis of the armature. Before simulating the armature, it is necessary to briefly analyze the excitation of the whole model. In this paper, the drive coil current is selected as the object of analysis, and the variation of the current in the drive coil with time is shown in Figure.3.
4.2.1. Effect of armature material on the performance of electromagnetic transmitters

The material of the armature essentially determines the permeability and conductivity of the armature and plays a decisive role in the acceleration performance of the electromagnetic transmitter, so the material of the armature should be the first consideration in the process of designing the armature of the transmitter. In this paper, several types of commonly used conductors are selected as armature materials, and the armature speed variation of different materials is simulated, and the results are shown in Table.1.

Table.1 End velocities of armature projectiles of different materials

| Armature material | End velocity of projectile |
|-------------------|---------------------------|
| Lead              | 3.2717 m/s                |
| Zinc              | 5.7143 m/s                |
| Aluminum          | 6.6610 m/s                |
| Copper            | 6.9655 m/s                |
| Silver            | 7.0684 m/s                |

From the point of view of economy and effectiveness of armature design, it is necessary to choose the material with good acceleration performance, but also to consider the cost. From the data in Table.1, it can be seen that the selection of copper as the armature material can achieve high acceleration performance requirements while not being too costly.

4.2.2. Effect of armature axial length on the performance of electromagnetic transmitter

The axial length of the armature is determined by the profiled area of the armature, and it is easy to see that the larger the area, the more the magnetic flux through the armature increases, and the more sensitive it is to changes in the magnetic field strength of the drive coil. In this paper, based on the initial model armature axial length of 60 mm, the armature axial length is increased or decreased, and the armature speed variation under different conditions is simulated, and the results are shown in Table.2.

Table.2 End velocities of armature projectiles with different axial lengths

| Axial length of armature | End velocity of projectile |
|-------------------------|----------------------------|
| 50 mm                   | 0.4852 mm/s                |
| 55 mm                   | 193.316 mm/s               |
| 60 mm                   | 6.9588 m/s                 |
| 65 mm                   | 9.4849 m/s                 |
| 70 mm                   | 11.3956 m/s                |

With Table.2, it can be concluded that the longer the armature axial length, the greater the armature end velocity and the better the acceleration performance of the coil-based electromagnetic transmitter will be. This is because when the armature axial length increases, the profile area of the armature increases, the magnetic flux passing through the armature cross section increases, the induced current...
in the armature is enhanced, the coupling between the armature and the drive coil is higher, the electromagnetic force on the armature is greater, and therefore the end velocity of the armature is greater, indicating better acceleration performance of the transmitter. In this simulation process, there is another point worth explaining, when the axial length of the armature is 50 mm, the final velocity of the armature is close to 0. This is because the axial length of the armature and the axial length of the drive coil are equal at this time, and it is known from the previous analysis that no matter how the current in the drive coil changes at this time, the electromagnetic force received by the armature is close to 0, and naturally, the purpose of acceleration cannot be achieved.

4.2.3. Effect of armature inner diameter on the performance of electromagnetic transmitter
The inner diameter of the armature affects the same profile area of the armature, which has a large impact on the performance of the transmitter. In this paper, different sizes of armature inner diameters are selected to simulate the change of armature speed under different conditions, and the results are shown in Table.3.

Table.3 End velocity of armature projectile with different inner diameters

| Inner diameter of projectile | End velocity of projectile |
|-----------------------------|---------------------------|
| 8 mm                        | 7.0763 m/s                |
| 9 mm                        | 6.9754 m/s                |
| 10 mm                       | 6.9007 m/s                |
| 11 mm                       | 6.8919 m/s                |
| 12 mm                       | 6.8173 m/s                |

With Table.3, it can be visualized that as the inner diameter of the armature increases, the end velocity of the projectile decreases and the acceleration performance of the electromagnetic launcher becomes better. This is because when the inner diameter of the armature increases while the outer diameter of the armature remains the same, the profile area of the armature decreases, the magnetic flux through the armature decreases, the induced current in the armature weakens, the coupling between the armature and the drive coil decreases, the electromagnetic force on the armature becomes smaller, and therefore the end velocity of the armature becomes smaller, indicating that the acceleration performance of the launcher is worse. However, the same graph shows that the end velocity of the armature changes when the inner diameter of the armature is changed, but the change in velocity is relatively small, which can be analyzed by the static magnetic field distribution of the coil gun in Figure.4.

![Figure.4 Schematic diagram of the static magnetic field distribution](image-url)
According to Figure 4, the distribution of the magnetic field of the drive coil in the armature is as follows: the magnetic field strength at a certain point in the armature and the radial distance between the point and the drive coil are inversely proportional to each other. The magnetic flux across the armature profile will be reduced, but the amount of reduction is not much, so the effect on the magnetic coupling between the armature and the drive coil is small, and naturally the effect on the end speed of the armature is also small.

4.2.4. Effect of armature outer diameter on the performance of electromagnetic transmitter

The outer diameter of the armature determines the width of the air gap between the armature and the drive coil, which has a large impact on the performance of the transmitter. In this paper, different sizes of armature outer diameters are selected to simulate the armature speed variation under different conditions, and the results are shown in Table 4.

| Outer diameter of projectile | End velocity of projectile |
|-----------------------------|---------------------------|
| 28 mm                       | 6.2877 m/s                |
| 29 mm                       | 6.7563 m/s                |
| 30 mm                       | 7.0763 m/s                |
| 31 mm                       | 7.7693 m/s                |
| 32 mm                       | 8.6113 m/s                |

According to Table 4, it can be concluded that the larger the outer diameter of the armature, the greater the end velocity of the projectile and the better the acceleration performance of the electromagnetic launcher. When the inner diameter of the armature remains the same while the outer diameter increases, the profiled area of the armature increases, the magnetic flux through the armature increases, the induced current in the armature is enhanced, the coupling between the armature and the drive coil becomes better, the electromagnetic force on the armature becomes larger, and therefore the end velocity of the armature is greater, indicating better acceleration performance of the launcher. At the same time, it can be observed that the final velocity of the projectile changes more when the outer diameter of the armature is changed, and this phenomenon is more obvious when the outer diameter of the armature is larger. is relatively large, and naturally the effect on the end velocity of the projectile is stronger.

5. Conclusion

Based on the above analysis, it can be concluded that: when selecting the armature material, the conductivity and permeability should be fully considered, and the material of the armature should be reasonably selected in combination with the cost factor; when the axial length of the armature is larger than the length of the drive coil, the larger the axial length of the armature, the better the acceleration performance of the electromagnetic transmitter, and the axial length of the armature should be reasonably selected in combination with the actual size of the projectile; the inner diameter of the armature has less influence on the performance of the electromagnetic transmitter when the radial thickness of the armature is larger. The inner diameter of the armature has less influence on the performance of the electromagnetic launcher when the radial thickness of the armature is larger, and the study of the outer diameter of the armature is also a study of the influence of the air gap between the armature and the drive coil on the acceleration performance of the launcher, and the outer diameter of the armature should be increased and the inner diameter of the armature reduced as much as possible under the condition of ensuring safety and considering the cost.

The research content of this paper provides a theoretical basis for the armature design of coil gun, which is of great reference significance for improving the acceleration performance of coil gun.

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