Study on the influence of different thickness of armature structure on the emission performance of electromagnetic induction coil launcher

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Abstract, In the armature structure of traditional electromagnetic induction coil launcher, the armature tail melted due to heat accumulation. In this paper, three new armature structures are proposed. Based on the finite element software maxwell2D, the single-stage electromagnetic induction coil launcher, model is established. The performance indexes of traditional and new armature structures are compared, and the influence of the thickness of traditional armature structure and the side thickness of new structure on temperature rise and electromagnetic performance is studied. On the basis of Maxwell-thermal finite element, the correctness of the temperature field conclusion is verified. The simulation results show that the traditional armature structure has the optimal thickness and the armature performance remains unchanged when the weight ratio and the mechanical strength of the armature are considered. Structure 3 and Structure 4 of the new structure significantly improve the temperature rise of the armature and enhance its emission performance. Due to the eddy current, the optimum side thickness of the new structure 3 and structure 4 is slightly larger than 1/2 of the armature length.

1. Introduction
In the test of the electromagnetic induction coil launcher, with the increase of induction coil series or under continuous launch conditions, the tail of armature melted due to the accumulation of heat [1-3], and the temperature rise of armature became an important factor that restricts the launch performance of coil launcher [4]. The known factors affecting the temperature field of armature include: initial position of armature, material and structure of armature [5]. At present, there is little research on the influence of armature thickness on temperature field [6]. In this paper, armature structure is optimized from the angle of armature thickness to improve the emission performance of electromagnetic induction coil launcher, and the relationship between armature thickness and emission performance of single-stage electromagnetic induction coil launcher is obtained.

In this paper, based on the model of single-stage electromagnetic induction coil launcher, the mathematical model of force, displacement and temperature field of electromagnetic induction coil launcher is established, and the influence of armature thickness on the launch performance of single-stage electromagnetic induction coil launcher is studied by using finite element analysis software ANSYS. At the same time, the temperature field of electromagnetic induction coil launcher changes in time and space, which belongs to transient temperature field [5], so the validity of the temperature field
conclusion is verified by Maxwell-therma joint simulation.

2. Mathematical model:

2.1 thrust equation\(^[7]\):

It is known that the magnetic energy stored in the current-carrying conductor is related to the inductance of the system, which is the cross-linked magnetic flux per unit current in the circuit. Therefore, based on this theory, the total energy storage of electromagnetic induction coil launcher system is:

\[
W_m = \frac{1}{2} \sum_{j=1}^{m} L_j i_j^2(t) + \frac{1}{2} L_0 i_0^2(t) + \sum_{j=1}^{m} M_j i_j(t) i_0(t)
\]  

(1)

Assuming that the object moves along the X direction, the motion ignores the influence of gravity and air resistance, the magnetic energy of the self-inductance term does not change, only the magnetic energy of the mutual inductance term changes with X. Excluding other energy losses, the force acting on the object at time \(t\) along the X direction is:

\[
F(t) = \frac{dW_m}{dx} = \sum_{j=1}^{m} \frac{dM_j}{dx} I_j(t) I_0(t)
\]  

(2)

Medium formula, \(L_j, i_j\) are the inductance of the armature, the current induced in the armature, \(L_0, i_0\) are the inductance of the driving coil, and the total current of the driving coil; \(M_j\) is the mutual inductance between armature and drive coil. \(W_m\) is the total energy storage of synchronous induction coil transmitter system.

2.2 Displacement equation:

According to Newton’s second law and thrust equation, the object acceleration is obtained:

\[
a(t) = \frac{F(t)}{m_a} = \frac{1}{m_a} \sum_{j=1}^{m} \frac{dM_j}{dx} I_j(t) I_0(t)
\]  

(3)

object velocity at time \(t\) from which the object can be deduced:

\[
v(t) = \int_0^t a(t) dt
\]  

(4)

Medium formula, \(m_a\) is the object mass. \(A(t)\) is the acceleration at time \(T\).

2.3 temperature field control equation

The temperature field of electromagnetic induction coil launcher during launch belongs to transient temperature field. The electromagnetic coil launcher itself is a heat conductor with heat source which mainly transfers heat to the coil transmitter by means of thermal convection and heat conduction. It is a comprehensive process of heat conduction and convection heat exchange\(^[5]\). Convective heat transfer refers to the phenomenon of heat transfer between fluid and solid surface when fluid flows through solid. Convective heat transfer relies on the movement of fluid particles to transfer heat, which is closely related to the fluid flow.

Strength basis of convective heat transfer newton law of cooling\(^[8]\):

\[
q = hS(T - T_f)
\]  

(5)

Medium formula, \(q\) is the heat exchanged between solid surface and fluid per unit area in unit time, which is called heat flux density, \(T, T_f\) are the temperature of solid surface and fluid respectively. \(h\) is called heat transfer coefficient, which indicates the heat transferred per unit time when the temperature difference between the fluid and the solid surface is 1K on the solid surface per unit area, \(h\) reflects the strength of convective heat transfer.
3. Finite element simulation:

3.1 Simulation parameter setting

One of the most widely used armature cross-sectional shapes in electromagnetic coil launcher simulation is rectangle, and the electromagnetic induction coil launcher can be regarded as an axisymmetric structure. Most of the armature models studies are equivalent to rectangle under maxwell-2D axisymmetric [9]. In this paper, only the simulation model in half yz plane (shown in Figure 1) is given. Using Maxwell 2-D simulation environment, according to the model simulation results, the transient temperature field is introduced for simulation. The simulation parameters of single-stage electromagnetic induction coil launcher are shown in Table 1.

![Fig. 1 Schematic diagram of structure of induction coil and armature](image)

**Table 1 Model parameters**

| Component name | parameter                      | numerical value |
|----------------|--------------------------------|-----------------|
| Power Supply   | Capacitance /mF                | 20              |
|                | Initial capacitance voltage /kv| 1.7             |
|                | Loop resistance/m              | 2.5             |
| drive coil     | Coil inner diameter /mm        | 165             |
|                | number of windings             | 24              |
|                | Coil length /mm                | 100             |
| armature       | Outer diameter of armature /mm | 160             |
|                | Armature length /mm            | 100             |

3.2 Influence of traditional armature thickness on emission performance

Under the model of single-stage electromagnetic induction coil launcher, if the structure of the armature and the drive coil are unchanged, the radial distance between the drive coil and the armature will be unchanged, and the external circuit parameters are unchanged, etc. The armature thickness is simulated from 1-14 mm. Study the influence of different thickness of traditional armature on temperature rise and emission performance.

Since there are too many simulation curves, it is difficult to observe the law, and the curve change trend and frequency of the simulation results are basically the same, so the armature force and eddy current loss in the electromagnetic propulsion process are compared at the peak point and the armature speed with the outlet speed.
As shown in Figure 2 and Figure 3, the thickness of the armature is 1-7mm. During the electromagnetic propulsion process, the thrust and speed of the armature increase with the increase of the thickness of the armature. When the thickness of the armature exceeds 7 mm, the thrust and speed of the armature remain basically unchanged during this process, indicating that the armature thickness has an optimal value when the weight ratio of the armature to the object is considered and the mechanical strength of the armature is not affected. At the same time, in maxwell simulation, it is found that the thicker the armature, the smaller the difference between the peak armature speed and the outlet speed.

Analysis: Without changing the distance between the armature and the driving coil, as the thickness of the armature increases, the current cross-section of the armature becomes larger, the flux linkage becomes smaller, and the mutual inductance gradient between the armature and the induction coil decreases accordingly until the thickness is greater than the optimal value, the mutual inductance gradient between the armature and the induction coil is basically unchanged, the force on the armature is basically unchanged, and the exit speed of the armature is basically unchanged.
As shown in Figure 4. It can be seen that the thickness of the armature is 1-7 mm, and during the electromagnetic propulsion process, the eddy current loss decreases with the increase of the thickness of the armature. When the thickness of the armature exceeds 7 mm, the eddy current loss during the electromagnetic propulsion does not change with the change of the thickness of the armature, which indicates that the thickness of the armature considers the weight ratio of the armature to the object and does not affect the mechanical strength of the armature. Eddy current loss directly affects the armature temperature rise, that is, there is a suitable armature thickness to minimize the armature temperature rise. 

Analysis: The eddy current heat generation is the main source of armature heat loss, and the eddy current causes skin effect [10]. When the armature reaches a certain thickness, that is, beyond the depth of skin effect, the eddy current heat generation effect is not obvious, and increasing the armature thickness will increase the weight ratio of armature object instead.

3.3 Comparison of emission performance between new structure and traditional structure

As mentioned before, the thickness of armature affects the emission performance of electromagnetic induction coil launcher. Rectangular section armature is one of the most widely used armature section shapes in electromagnetic induction coil launcher test. To avoid skin effect and armature tail heating, the thickness of the armature tail can be appropriately increased. Therefore, several new structures are proposed in this paper (as shown in Figure 5). The Structure 1 is the traditional armature section structure, and Structure 2, 3 and 4 appropriately increase the thickness of the armature tail on the basis of the first structure. The effects of four structures on emission performance are compared, and the influence of the thickness of the lower side of the new structure on temperature rise is studied.
As shown in Figure 6 – Figure 8, the comparison of emission performance of four different structures shows that the Structure 3 and Structure 4 have significantly improved the speed, force and eddy current loss of the armature during electromagnetic propulsion. Therefore, to avoid skin effect and armature tail heating, the thickness of armature tail can be appropriately increased.
As mentioned above, the armature thickness of the conventional structure (Structure 1) has an optimal value, so the influence of the thickness of the underside of the new structure (as shown in Fig. 5) on the emission performance is considered. Because structure 3 is similar to structure 4, the results of armature force, velocity and eddy current loss in the simulated structure are basically the same, so structure 3 is selected for research. The thickness of the armature side of structure 3 is simulated once at 10mm intervals from 10-100mm, and the following conclusions are obtained.

As shown in Figure 9, Figure 10 and Figure 11. It can be seen that the armature speed, force and eddy current loss of the electromagnetic induction coil launcher are basically unchanged when the thickness of the armature side exceeds 60mm under the new structure. It shows that the armature side thicknesses of structure 3 and structure 4 also have optimal values, or the bottom area of the new structure, considering the weight ratio of the armature to the object and without affecting the mechanical strength of the armature.
Fig. 9 Force change curve during electromagnetic propulsion

Fig. 10 Speed change curve of electromagnetic propulsion

Fig. 11 Variation curve of eddy current loss during electromagnetic propulsion

Analysis: As the eddy current induced by the armature is acted by Lorentz force in the transient magnetic field, which pushes the armature forward, and the eddy current is concentrated at the bottom of the armature. Under the new structure, when the thickness of the side is far greater than the range of
eddy current generation, the eddy current has little effect on the thrust of the armature, so the outlet speed of the armature does not change much. The corresponding eddy current loss is also concentrated in the tail of the armature. Therefore, when the thickness of the side is much larger than the eddy current range, it has little influence on the armature temperature rise.

3.5 Maxwell-thermal temperature field conclusion verification

The above results show that the traditional armature and the underside of the new structure have the optimum thickness. In order to verify the correctness of the temperature-thickness conclusion, the Maxwell 2-D simulation environment is used, and the transient temperature field is introduced according to the simulation results of the model. The average temperature rise of the armature is as follows (see Figures 12 and 13). In the simulation, the ambient temperature is set at 20°C and the convective heat transfer coefficient is set at 20 \( \text{W/(m}^2\cdot\text{°C}) \)

The results show that there is an optimum armature thickness under the traditional structure (structure 1). When the thickness of armature exceeds 7mm, the average temperature rise of armature is basically unchanged. Similarly, under the new structure (structure 3), the average temperature rise of the armature is basically unchanged after the armature thickness exceeds 60 mm. It shows that the appropriate armature thickness will greatly improve the average temperature rise of the armature regardless of the new and old structures. The correctness of the conclusion of thickness-temperature is verified.

![Fig. 12 Graph of armature thickness and temperature rise of traditional structure (structure 1)](image1)

![Fig. 13 Graph of armature thickness and temperature rise of new structure (structure 3)](image2)
4. Conclusion:
In this paper, the mathematical model of thrust, velocity and temperature of the single-stage electromagnetic induction coil launcher is established, and the analysis software of thrust, velocity and temperature is studied from the angle of armature thickness using Ansoft-Maxwell electromagnetic field finite element analysis. At the same time, considering that the rising temperature of the armature is an important factor restricting the launch performance of the coil launcher, several possible shapes of the armature of the electromagnetic induction coil launcher are proposed for simulation and comparison, and the following conclusions are drawn:

1. The traditional structure (structure 1) has an influence on the temperature, force and speed, and there is an optimal armature thickness. Proper armature thickness can not only reduce the weight ratio of the armature in the object but also not affect the mechanical strength of the armature.
2. To avoid skin effect and armature tail heating, a new structure is proposed. There is also an optimal value of the side thickness under the new structure, or it is related to the bottom area of the new structure.
3. By analogy, the improvement of armature structure can also be extended to the optimization of induction coil, for example, from the winding mode and structure of induction coil.

Obviously, the launch performance of the electromagnetic induction coil launcher can be optimized by reasonably increasing the thickness of the armature. In order to verify the standard of the simulation results, the next step will be to measure the temperature rise of the armature in the experiment to provide guidance for the subsequent electromagnetic induction coil launch experiments.

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