Armature Performance Comparison of an Induction Coil Launcher

Yadong Zhang, Jiangjun Ruan, Ying Wang, Yujiao Zhang, and Shoubao Liu

***Abstract*—This paper focused on the verification of the current filament method and the performance comparison of different armatures. Armature has as much influence on the performance of a coil launcher as any other major subsystem. The design of an armature is influenced by a large set of highly coupled parameters. The sleeve armature is a common choice for experiment and analysis of a coil launcher. The current filament method is widely used to analyze the sleeve armature. However, due to skin effect, the current distribution will be inconsistent, and excessive heating will be caused in the sleeve armature. How to use the current filament method accurately should be considered. Another good choice is the solenoid armature, which can make current and temperature distribution uniformly. To verify the current filament method and compare the performance between a sleeve armature and a solenoid armature, several kinds of projectiles were constructed and tested, including a sleeve projectile, a 24-turn copper-ring projectile, a 20-turn wire-ring projectile, and a 20-turn solenoid projectile. Then, 2-D finite-element simulations based on the experiments were taken to further study the problems. It is shown that in the sleeve armature (including multiturn ring armature) most of the induced current tend to distribute unevenly in the armature. Over concentration of the current will cause excessive heat and limit the material, structure, velocity, and efficiency of the sleeve armature. The sleeve armature must be divided into enough number of filaments; otherwise, the current filament method may be invalid. A solenoid armature can solve these problems by distributing the induced current evenly. However, fabrication of the solenoid armature becomes another difficulty. Further analysis of the current density in the solenoid armature shows that the skin effect will work in the wire of the solenoid, but it has little influence on the system performance. A detailed description of the experiments and simulations will be presented in this paper.**

***Index Terms*—Armature, current filament method, sleeve, solenoid.**

I. Introduction

A COAXIAL induction coil launcher usually consists of a conductive armature and a barrel formed by an array of coils. The coils of the barrel are fed in sequence by a set of capacitor-driven circuits. Armature currents are induced in an attempt to exclude magnetic flux from the armature. The interaction of the net radial magnetic field with the azimuthal armature current results in an axial force that accelerates the armature [1]–[5].

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The armature has as much influence on the performance of a coil launcher as any other major subsystem. The sleeve armature (monolithic single-turn projectile) is a common choice for experiment and analysis of a coil launcher. The current filament method is widely used to analyze the sleeve armature. However, due to skin effect, the current distribution will be inconsistent, which will cause excessive heating in the sleeve armature. It is incorrect to assume that the currents distribute uniformly throughout the sleeve armature. How to use the current filament method accurately should be considered. The problem will be discussed by experiment and simulations in this paper.

Over concentration of the induced current in the sleeve armature will cause excessive heating. To solve the problem, solenoid armatures that have uniform current density were constructed [6], [7]. The solenoid armature could withstand field reversal and maintain low temperature [6], [8]. Performances of a sleeve armature and a solenoid armature are compared by experiment and simulation in this paper. Further analysis of the current density in the solenoid armature shows that the skin effect will work in the wire of the solenoid, but it has little influence on system performance.

II. Current Filament Method

In an induction coil launcher, forces are characterized by the currents and the variations in the mutual inductance between armature and coils. The mutual inductance could be determined using the current filament method described in [7]. It assumes an axisymmetric accelerator geometry. The set of equations can be derived by considering the induction acceleration of a circular filament, driven in a repulsion mode by another concentric circular filament subjected to an arbitrarily varying voltage. The equivalent circuit of an induction coil launcher based on the current filament method is shown in Fig. 1.

Employing Kirchhoff's law, the network equations of the ith stator coil is expressed

$$R_{ci} I_{ci} + L_{ci} \frac{dI_{ci}}{dt} + \sum_{k=1}^{i-1} M_{ccki} \frac{dI_{ck}}{dt} + \sum_{j=1}^{m} \frac{d}{dt}(M_{caij} I_{aj}) = U_i \tag{1}$$

where

$$U_i = U_{i0} - \frac{1}{C_i} \int_{t_i}^{t} I_{ci}\, dt, \qquad t \geq t_i. \tag{2}$$

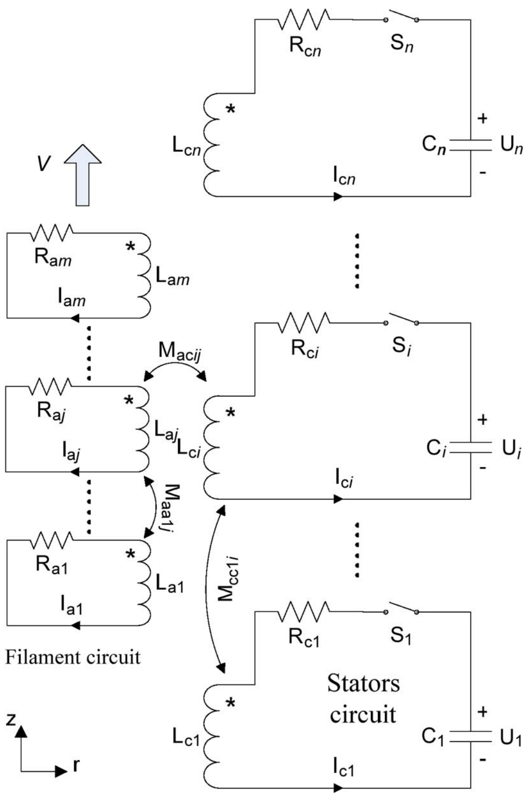


Fig. 1. Current filament model of the induction coil launcher.

The network equation of the jth filament is expressed as

$$R_{aj}I_{aj} + L_{aj}\frac{dI_{aj}}{dt} + \sum_{k=1}^{i}\frac{d}{dt}(M_{ackj}I_{ck}) + \sum_{k=1,k\neq j}^{m} M_{aajk}\frac{dI_{ak}}{dt} = 0. \quad (3)$$

The force on the armature is expressed as

$$F_z = \sum_{i=1}^{n}\sum_{j=1}^{m} I_{ci}I_{aj}\frac{dM_{acij}}{dz} \quad (4)$$

where

U_i voltage applied to the ith coil;
R_{ci} resistance of the ith coil;
R_{aj} resistance of the jth armature;
L_{ci} self-inductance of the ith coil;
L_{aj} self-inductance of the jth armature;
M_{ccki} mutual inductance between the ith and kth coil;
M_{aajk} mutual inductance between the jth and kth armature;
M_{caij} mutual inductance between the ith coil and the jth filament;
I_{ci} current in the ith coil;
I_{ck} current in the kth coil;
I_{aj} current in the jth filament;
I_{ak} current in the kth filament.

To verify the current filament method, a copper sleeve projectile and a 24-turn copper-ring projectile were manufactured, which are shown in Fig. 2. The two projectiles have the same effective conductor length of 120 mm and mass of 0.37 kg. The copper sleeve projectile is composed by a 120-mm sleeve armature and a polyvinyl chloride (PVC) tube, which are glued together. The 24-turn copper-ring projectile is composed of 24 filament elements, 5 mm in length. The filament elements are fixed on a PVC tube, and the adjacent elements are insulated with insulating adhesive tapes. Both of the two projectiles were impelled by the same single coil, which is shown in Fig. 3. The coil was powered by 2.4-mF capacitors with voltage of 1.5 kV. The velocities measured of the copper sleeve projectile and the 24-turn copper-ring projectile are 7.3 and 6.9 m/s, respectively.

Then, based on the experiment, 2-D finite-element simulation models were constructed, as shown in Fig. 4(a). The copper sleeve armature and the 24-turn copper-ring armature are shown in Fig. 4(b) and (c). The velocities simulated of the sleeve armature and the 24-turn copper-ring armature are 8.1 and 7.7 m/s, respectively. Taking friction, noncoaxial, and other factors into consideration, the simulation results are thought to be correct in comparison with the experiments. For further analysis of the current filament method, a 240-turn copper-ring

(a) (b)

Fig. 2. Projectiles manufactured for the experiment. (a) Sleeve armature projectile. (b) Twenty-four-turn copper-ring projectile.

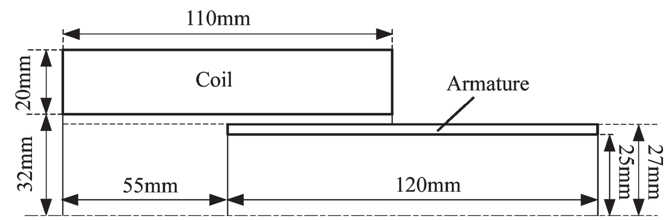
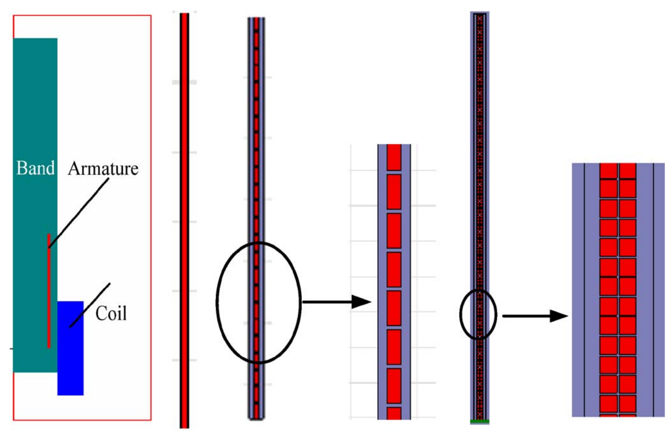


Fig. 3. Single-stage coil launcher in the sleeve armature experiment.



(a) (b) (c) (d)

Fig. 4. Two-dimensional simulation model for the current filament method. (a) Simulation model of the experiment. (b) Simulation model of the sleeve armature. (c) Simulation model of the 24-turn copper-ring armature. (d) Simulation model of the 240-turn copper-ring armature.

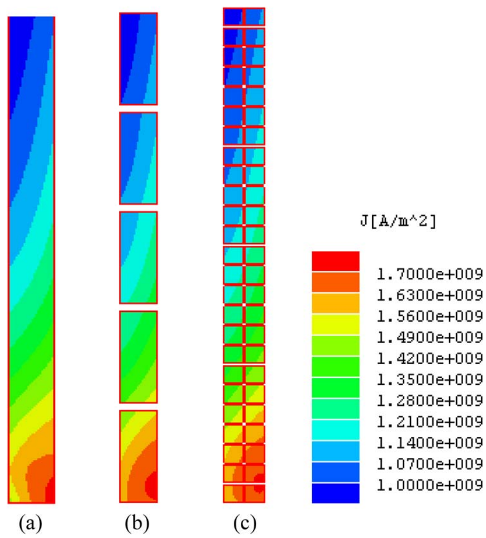


Fig. 5. Current density in the rear of the armature at 0.0005 s. (a) Current density in the rear of the sleeve armature. (b) Current density in the rear of the 24-turn copper-ring armature. (c) Current density in the rear of the 240-turn copper-ring armature.

armature was simulated in Fig. 4(d). The sleeve armature is divided into 240 elements (120 in the axial direction and 2 in the radial direction) to detail the current distribution. The cross section of the filament is a square with sides of 1 mm. The filament element is sufficiently thin to make the current density distribute evenly in the cross section. The simulated velocity is 7.4 m/s. Clearance between the filament elements will change the whole length of the armature, which should be responsible for the difference of the three simulated velocities.

The current density in the rear of the different armatures at 0.0005 s is shown in Fig. 5. In general, the current distribution patterns of the three armatures are very similar. Due to skin effect, the current distribution is inconsistent, and excessive heating will be caused in the rear of the sleeve. If the current filament element is small enough, then the current in the cross section will be relatively uniform. The current distribution in Fig. 5(c) is more uniform with that in Fig. 5(b). Thus, to analyze the performance of a coil launcher accurately, the sleeve must be subdivided slender enough in the radial and axial directions, particularly in the rear of the armature. Fig. 5 shows another conclusion that the time-varying magnetic field in the radial direction has little influence on the current distribution. It means that there is little or no eddy current on the surface of the armature in the axial direction.

The sleeve armature must be divided into enough number of filaments; otherwise, the current filament method may be invalid.

III. Solenoid Armature

Over concentration of the current in the sleeve (multiturn ring armature can be seen as another type of sleeve armature) will cause a temperature rise, which tends to exceed the melting point of the material and destroy the mechanical performance. It is a significant restriction to the development of the coil launcher.

Fig. 6. Projectiles manufactured for the experiment. (a) Twenty-turn solenoid projectile. (b) Twenty-turn wire-ring projectile.

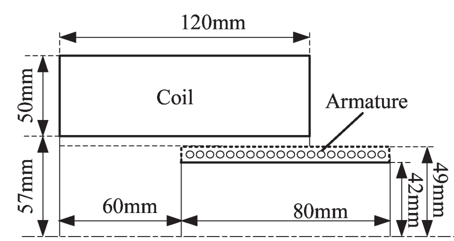


Fig. 7. Single-stage coil launcher in the multiturn armature experiment.

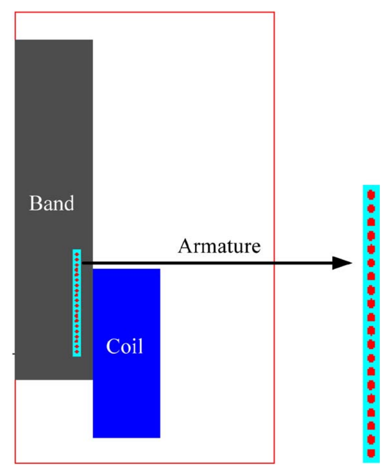


Fig. 8. Two-dimensional model for the wire armature comparison.

To limit the extreme current distribution, a solenoid armature has been constructed [6]–[8]. To compare the performance of a sleeve armature and a solenoid armature, two multiturn wire projectiles were constructed with the same mass of 0.29 kg and the same conductive area, which is shown in Fig. 6. A 20-turn solenoid projectile was manufactured with a single wire winding around a PVC tube, the ends of which are welded at center line, as shown in Fig. 6(a). A 20-turn wire-ring projectile was constructed with 20 wire rings tied around a PVC tube. The ends of each wire ring are welded and fixed at the surface of the PVC tube, as shown in Fig. 6(b). Both of the two projectiles were impelled by the same single coil, which is shown in Fig. 7. The coil was powered by 19-μF capacitors with voltage of 15 kV. The velocities measured of the solenoid projectile and the 20-turn wire-ring projectile are 6.7 and 5.3 m/s, respectively.

Then, 2-D finite-element simulation models based on the experiment were constructed, as shown in Fig. 8. The velocity simulated of the 20-turn wire-ring projectile is 6.2 m/s, which is greater than the experiments. In addition to the factors of

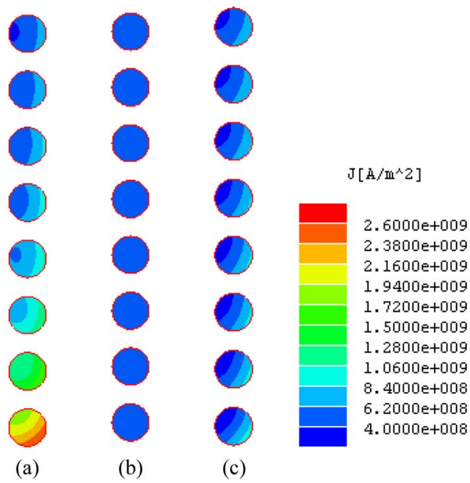


Fig. 9. Current density in the rear of the armature at 0.0005 s. (a) Current density of the 20-turn wire-ring armature. (b) Current density of the 20-turn strand solenoid armature. (c) Current density of the 20-turn solid solenoid armature.

friction and noncoaxial, mechanical construction should be responsible for the inaccuracy of the experiment. Due to the poor fixation of the wire rings, the wire-ring projectile had been distorted in shape several times during the experiment.

To research the solenoid armature, two models were considered. One is the strand armature, whose wire is considered to be of filaments too thin to model in a practical finite-element grid. Eddy currents and displacement currents are not computed inside the conductor. Because of this, the transient solver in Ansoft assumes that their contribution to the current density is averaged over the area of the problem region. A uniform current density is assumed throughout the conductor. Another model is the solid armature, whose wire is considered to be a solid conductor. The amounts of eddy current, displacement current, and source current are included in the total current in the calculation. The velocities simulated of the strand armature and solid armature are 7.0 and 6.9 m/s, respectively.

The current density in the rear of the armatures at 0.5 ms is shown in Fig. 9. Fig. 9(a) shows that the current density is quite non-uniform, particularly in the last wire ring. Comparing with the last ring of the 20-turn wire-ring armature, as expected, the solenoid armature could reduce the current density greatly. This type of armature can help control heating by reducing the current density and results in better performance. It could be proved by the velocity results. Fig. 9(b) shows the desired uniform current density. However, actually, Fig. 9(c) should be more correct due to the eddy current existing in the wire. The average current density of the solid conductor in Fig. 9(c) is nearly equal to the result of the strand conductor in Fig. 9(b). Both of the results are far less than the current density in the last wire ring of Fig. 9(a). The advantages of the solenoid armature will be remarkable in the high-speed design, whose temperature becomes a chief problem.

Although a solenoid armature has many advantages over a sleeve armature, mechanical construction is a thorny problem. To be practical, an armature must be able to survive the mechanical and electrical stresses during launch. In addition to large acceleration forces that may try to shear the windings from the support structure, an armature will be subjected to a large crushing force that arises from the axial magnetic field in the air gap. This crushing force can be approximated as a magnetic pressure. The von Mises stress invariant is compared directly to the yield stress of the support material to determine if yield has occurred. Another problem of a solenoid armature is that energy has to be graded at start-up and near-field reversal points to limit the voltage between turns to acceptable values when the flux changed rapidly. Due to the problems above, fabrication of a solenoid projectile consumes considerably more time than fabrication of a sleeve projectile. However, to achieve the goal of high-speed launching, it is worth our while to adopt the solenoid projectile.

IV. Summary of Results

In this paper, the current filament method has been discussed, and the performances of the sleeve armature and the solenoid armature have been compared.

It is proved that current filament method is workable. To accurately analyze the performance of a sleeve armature, the sleeve has to be divided into enough parts in the radial and axial directions. The slenderer the armature subdivided, the more uniform the current distributed in the filament. Time-varying magnetic field in the radial direction has little influence to the current distribution. It means that there is little or no eddy current on the surface of the armature in the axial direction.

A sleeve armature is easy to construct. However, the disadvantage of this type of armature is clearly that the current distribution is very nonuniform due to skin effect. It will cause a temperature rise that limits the development of the coil launcher. Comparing to a sleeve armature, a solenoid armature will greatly reduce the current density, even taking skin effect into account. This type of armature can help control heating and achieve better performance. A solenoid armature must form a closed electrical circuit that will cause some interesting fabrication challenges. However, to achieve the goal of high-speed launching, it is worth our while to adopt the solenoid projectile.

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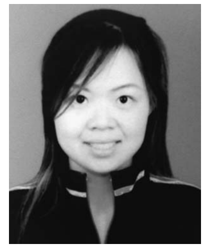

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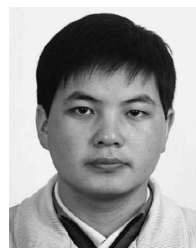

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