

A Simplified Numerical Approach for Simulating Electromagnetic Propulsion

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Abstract

Electromagnetic propulsion provides a non-contact way for delivering goods. The projectile typically does not contain explosives, which has apparent advantages over traditional methods. Due to the multi-physics nature, simulation is expensive and time-consuming. We established a simplified model in time domain incorporating mechanics and electromagnetics to study electromagnetic propulsion. Results show that important physical parameters such as force, velocity, acceleration, etc. can be extracted from the model without time-consuming efforts. We hope this model could help the exploration of electromagnetic propulsion.

Keywords

Electromagnetic Propulsion, Gaussian Law, Numerical Simulation

1. Introduction

Electromagnetic propulsion uses the physics of moving charge or current conductor in a magnetic field under the electromagnetic force (known as Lorentz force) to accelerate the projectile [1] [2] [3]. This technology has been applied in different scenarios. For example, electromagnetic catapult is the newest generation of aircraft carrier special aircraft catapult being developed by navies of the United States, Britain, China and other countries [4] [5] [6]. Like a maglev train, an electromagnetic catapult uses a linear motor as its power source, which is apparently different from a traditional steam catapult. One of the advantages of an electromagnetic catapult is that it is safer to operate because it accelerates more evenly and does less structural damage as often occurs in a steam catapult. Moreover, electromagnetic propulsion allows large payloads over short distances from propulsion system, enabling its broad applications in military, civil and

industrial fields. Different from the traditional launching systems, such as the gunpowder gas pressure, electromagnetic propulsion uses the force of electromagnetic field, and its action time is much longer. It greatly improves the speed and range of the projectile, attracting the attention of scientists and engineers all over the world [7] [8].

However, we found that a simplified but accurate simulation is not currently available for studying electromagnetic propulsion. Here, we build a transient electromagnetic propulsion model in three dimensions by employing multi-physical fields. An initial test with a simplified armature shows that the speed can be accelerated to 1836 meters per second in our model. This model is simple but provides enough details in an intuitive way.

2. Theory

The entire magnetic propulsion problem involves mechanics, electromagnetics, aerodynamics, heat transfer etc. However, we only focus on electromagnetics and mechanics in this work. Heat transfer and aerodynamics can be added in further investigations in more details.

Due to the quasi-static nature of the problem under study, we can decouple the electromagnetic problem into pure electric and magnetic parts. In the electric domain, the governing equation is the Gaussian law [9] [10].

$$\begin{cases} \nabla \cdot \mathbf{J} = Q \\ \mathbf{J} = \sigma \mathbf{E} + \frac{\partial \mathbf{D}}{\partial t} \\ \mathbf{E} = -\nabla V \end{cases} \quad (1)$$

where \mathbf{J} is the current density in units of A/m², \mathbf{D} is the electrical displacement in unit of C/m², σ is the electrical conductivity in unit of S/m and V is the scalar potential in unit of V. For the electrical part, we only consider the two rails and the space in between them with other space ignored, since the electric field outside this region is not of interest to us. Simulations on these regions can give us the correct results regarding total current and local current density.

In the magnetic domain, the governing equation is the Ampere's law shown below with \mathbf{H} and \mathbf{A} being the magnetic field A/m in unit of and vector potential in unit of T-m, respectively [9] [10].

$$\begin{cases} \nabla \times \mathbf{H} = \mathbf{J} \\ \mathbf{B} = \nabla \times \mathbf{A} \end{cases} \quad (2)$$

Since magnetic field is generated by the current, there is no source nor sink for it. We incorporated a larger air region to cover the rails. The outer boundary of the air region is set to be magnetic insulation, namely, $\mathbf{n} \times \mathbf{A} = \mathbf{0}$, where \mathbf{n} is the surface normal.

The mechanics part is governed by the Newton's law below.

$$\frac{d^2 x}{dt^2} = \frac{F_x}{M} \quad (3)$$

$$F_x = \int_V (J \times B) dV . \quad (4)$$

3. Model and Results

The schematic diagram of electromagnetic propulsion system is shown in **Figure 1**. As shown, the whole simulation region consists of four components, including an outer air cylinder, two electrical conductive rails, the armature (not shown between the two rails). The outer air was used due to the transient nature of the electromagnetic wave applied. It is chosen to be large enough to make sure the electromagnetic field terminates at the outmost shell and does not have negative effect on the simulation. High current is applied along the two rails connected through the armature, with one forward-going and the other backward-going forming a current loop. The current also creates a magnetic field inside the loop. According to the right-hand helix rule, the magnetic field circulates around each conductor. On the other hand, the direction of the current between each orbit is relative, the magnetic field in the network between the rails is perpendicular to the plane of the axis centered on the orbit and the projectile. By interacting with the electric current in the armature, a Lorentz force is created, which forces the armature to accelerate and move straight along the rails until the armature leaves the rails. In this model, the separation of the rails under the influence of electromagnetic wave is not considered and is assumed to be perfectly fixed with mechanical mechanism. **Figure 2** shows the details regarding the mesh results. A finer mesh with element size one order of magnitude smaller than the air region is applied in the rails and the space in between.

Figure 3 shows the colored voltage distribution along the rails at different time snapshot, with the red lines denoting the magnetic field contours. A near 300 V voltage is needed for the electromagnetic propulsion system under study. It is clearly seen that the direction of the magnetic field in between the rails is oriented in the vertical direction perpendicular to the rails. To further study the kinetics of the armature, we plot the position, velocity and acceleration in **Figure 4**.

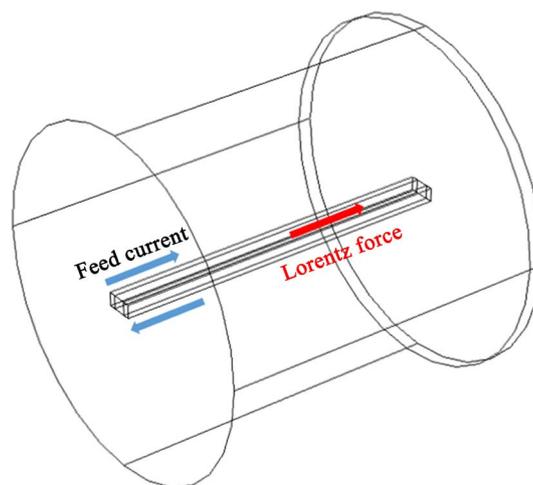


Figure 1. Schematic of the electromagnetic propulsion model under study.

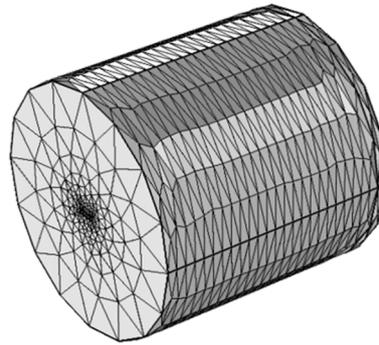


Figure 2. Mesh results of the electromagnetic propulsion model under study.

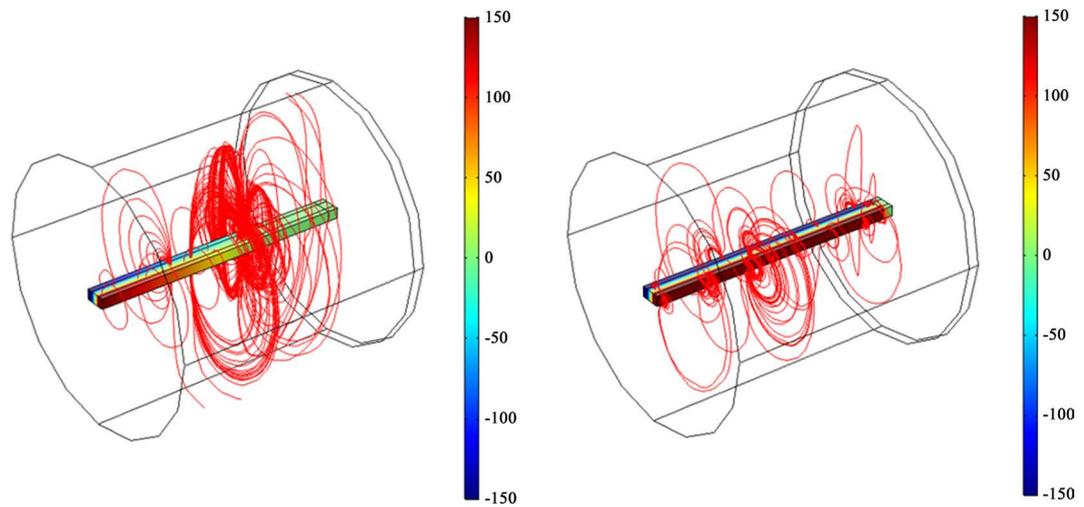


Figure 3. Voltage distribution of electromagnetic propulsion at $t = 0.002$ s (left), and $t = 0.004$ s (right). The streamline denotes the magnetic field.

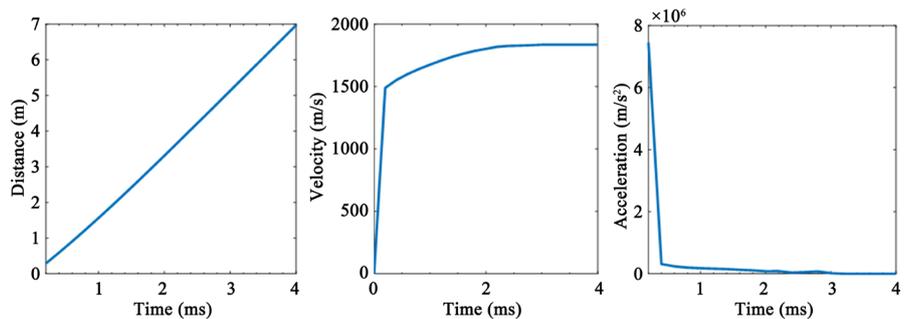


Figure 4. The position, velocity and acceleration of the conductive projectile as a function of time.

The armature travels about 7 meters in 4 milliseconds, reaching a speed of 1836 m/s. It gains tremendous acceleration during the interaction with electromagnetic wave.

4. Conclusion

In summary, we have built a simplified model for simulating electromagnetic propulsion with finite element method. The model incorporates mechanics and

low-frequency electromagnetics. Numerical results show that the electrical projectile can be accelerated to 1836 m/s in a traveling distance of 7 meters. In the future, more details, such as heat transfer effect, could be added to give even detailed and accurate results.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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