Research on electromagnetic propulsion system based on reusable space vehicle

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Abstract. It is inefficient and uneconomical to complete space launch mission with the assistance of unusable rockets which is the typically used approach today, and finding a more economical way has been the pursuit of scholars all over the world. According to the purpose above, this paper proposed a new design to lift a payload to the desired orbit. In this design, the electromagnetic propulsion system (EMPS) is applied to replace the first rocket, leaving the usable rocket to take care of the rest job. Based on this design, the structure of the propulsion system is constructed and the electromagnetic properties are analyzed by finite element analysis tool Maxwell, then the mathematic model of EMPS is simulated and calculated. The result shows that EMPS is capable of accelerating the vehicle, which weighs hundreds of tons, up to one hundred meters per second. Therefore, it is foreseeable that EMPS has a certain potential in the future space launch mission.

1. Introduction

Although technology is developing swiftly after entering the 21st century, the mature aerospace launch technology is still traditional one-time launch rocket. But the traditional rocket that relies on chemical energy has a critical weakness, that is, the ratio of the payload to the total take-off weight is quite small[1]. In the case of a Low-Earth Orbit (LEO) mission, the ratio mentioned above is usually only a few percent, while the implementation of the geostationary orbit (GTO) task corresponds to a lower ratio, or even less than one percent. Therefore, the completion of one launch mission requires a huge amount of money, transporting a kilogram of load into the LEO need to spend over four thousand American dollar[2]. And the traditional rocket releases harmful exhausts in the combustion process because of relying on the chemical energy, it contains pollution risk to the atmosphere. However, humans have never stopped thinking, scholars have been committed to finding a low-cost space launch technology, propose a variety of launching ideas in order to reduce the expenses, such as Skyhook[3], space elevator[4], reusable launch vehicle and electromagnetic propulsion system. These ideas have been carried out on different sizes of prototype construction, except space elevator. Among them, the electromagnetic propulsion system is one of the most practical concepts[5].

Electromagnetic launch technology developed rapidly and comprehensively for the past 20 years. Researchers not only concerned about the exit velocity of the emitter but also pay great attention to the weight of the emitter. Balikci A. and Zabar Z.[6] verified the possibility to launch missiles with large weight using electromagnetic force. Li Weibo and Cao Yanjie[7] also proposed a similar simulation model which launches missiles vertically using electromagnetic launch system. The United States Lake Hacker Naval Air Force Engineering Station successfully launched the T-45 Goshawk Trainer, C-2 Greyhound Transport and F/A-18 Hornet Fighter and other spacecraft, which makes the electromagnetic launch of large weight spacecraft into a new stage. From another point of view, it is
also feasible to launch large scale spacecraft with the application of electromagnetic propulsion technology.

2. Overall concept of EMPS

In this paper, the mathematical model of the coil electromagnetic propulsion system is established by using the equivalent current loop method. The usable launch vehicle is economically beneficial in that it can be recycled and will get ready for the next mission with necessary maintenance. Besides that, massive researches have been carried out by scholars [8] about reusable rockets and the conclusion that reusable vehicle is technically advisable can be drawn [9]. This paper takes the reusable vehicle as an object to be accelerated by EMPS based on the truth above.

![Figure 1. Overall concept of electromagnetic propulsion system.](image1)

![Figure 2. Schematic diagram of the equivalent current loop method for ignoring inter - stage coupling.](image2)

As it shows in figure 1, this paper presents a new approach to launch spacecraft to the given orbit. The concept consists of two parts, one is the spacecraft, and the other is the electromagnetic launch.

3. Electromagnetic launch system

Multi-stage coil electromagnetic launch concept is applied to electromagnetic launch device. Drive part of the system consists of 3000 coils and armature coil radial size is slightly smaller than the drive coil. In fact, the entire launch system can be considered as the composition of multi-stage induction coil linear motor. The drive coil is equipped with a guide rail, which can restrain the armature and vehicle combination, make them run smoothly on the propulsion line. The following is a mathematical model of the coil-type electromagnetic launch system.

The coil-type electromagnetic launch system is simple in structure, high in energy utilization, capable of propelling large-quality objects, and suitable for the propulsion task of spacecraft.

Assuming that the drive coil has n-stage, the capacitance, initial inductance, self-inductance, and resistance of each stage are \( C_i \), \( u_{ci} \), \( L_{di} \), and \( R_{di} \) (\( i = 1,2,\ldots,n \)), as it shows in figure 2. The self-inductance and resistance of the armature are \( L_p \), \( R_p \) and the mutual inductance of armature and drive coil is \( M_{dp} \).

The drive coil power supply in each stage triggers the discharge in turn, so assume that the armature moves to the trigger point of the stage \( i \) drive coil at \( t \), and the power supply of the stage \( i \) drive coil starts to trigger the discharge. Since the trigger switches of \( i+1,i+2,\ldots,n \) stage drive coils is in off state, the current in these coils is zero and the voltage across the capacitor is still the initial voltage. Then,

\[
\begin{align*}
u_{ck}(t) &= \frac{1}{C_i} \int_{0}^{t} i_{ck} \, dt \quad (k = 1,2,\ldots,i) \\
i_{ck} &= 0 \quad (k = i+1,i+2,\ldots,n)
\end{align*}
\]

The velocity of the armature can be acquired by solving equation (3),

\[
RI + L_pI - M_{dp} \frac{dM}{dx} = \begin{cases} 0 & (x < a) \\ U & (x \geq a) \end{cases}
\]
among them,
\[
R = \text{diag}(R_1, R_2, \ldots, R_n), \quad L = \text{diag}(L_1, L_2, \ldots, L_n)
\]
\[
I = \begin{bmatrix} I_p \\ I_{d1} \\ \vdots \\ I_{dn} \\ I_{di} \\ \vdots \\ I_{di} \\ I_{di} \\ \vdots \\ I_{di} \\ \vdots \\ I_{di} \\ I_{di} \\ I_{di} \end{bmatrix}, \quad \mathbf{M}_i = \begin{bmatrix} 0 & M_{d1,p} & \cdots & M_{d1,p} \\ & 0 & & & \\ & & 0 & \cdots & M_{d1,p} \\ & & & 0 & \cdots & M_{d1,p} \\ & & & & \ddots & \cdots & \vdots \\ & & & & & 0 & \cdots & M_{d1,p} \\ & & & & & & 0 & \cdots & M_{d1,p} \\ & & & & & & & 0 & \cdots & M_{d1,p} \\ & & & & & & & & 0 & \cdots & M_{d1,p} \\ & & & & & & & & & \ddots & \cdots & \vdots \\ & & & & & & & & & & 0 & \cdots & M_{d1,p} \\ & & & & & & & & & & & 0 & \cdots & M_{d1,p} \\ & & & & & & & & & & & & 0 & \cdots & M_{d1,p} \end{bmatrix}, \quad \mathbf{U} = \begin{bmatrix} u_{c1} \\ u_{c2} \\ \vdots \\ u_{cn} \end{bmatrix}
\]

The initial velocity and current of the armature are zero, so the initial current derivative of the moment is
\[
\dot{\mathbf{I}}_0 = (\mathbf{L}_0 - \mathbf{M}_0)\mathbf{U}_0
\]

The time step is \(\Delta t\), then the time series will be \(t_n (n=0,1,\cdots)\), so the current derivative at \(t_{n-1}\) is:
\[
\dot{\mathbf{I}}_{n-1} = (\mathbf{L}_{n-1} - \mathbf{M}_{I(n-1)})\mathbf{U}_{n-1} + v_{n-1} \frac{\mathrm{d}\mathbf{M}_{I(n-1)}}{\mathrm{d}x} \mathbf{I}_{n-1} - R\mathbf{I}_{n-1}
\]

Where, the component of \(\mathbf{U}_{n-1}\) is \(u_{i(n-1)} = u_{c(i(n-1))-1} \Delta t / C_{I_i}\), then the current \(\mathbf{I}_n\) at \(t_n\) is:
\[
\mathbf{I}_n = \mathbf{I}_{n-1} + \Delta\dot{\mathbf{I}}_{n-1}
\]

The axial electromagnetic force \(F_x\) received by the armature at \(t_n\) can be expressed as:
\[
F_x = \sum_{i=1}^{n} \left(\frac{\mathrm{d}\mathbf{M}_{d_i,p}}{\mathrm{d}x}\right) I_{d_i} I_p
\]

\(\left(\frac{\mathrm{d}\mathbf{M}_{d_i,p}}{\mathrm{d}x}\right)\) is the interaction gradient between the drive coil of stage \(i\) and the armature at \(t_n\),

\(I_{d_i}\) is the current of the stage \(i\) drive coil at \(t_n\),

\(I_p\) is the momentary current of the armature at \(t_n\).

In this paper, the drive coils at all stages are identical in structural parameters. Therefore, if the axial midpoint of the first stage drive coil is used as the reference origin, the mutual inductance function between the drive coils and the armature coils at each stage can be regarded as a function of the reciprocal function relative to the reference origin translation. If it is assumed that the position of \(i\)-th drive coil is \(x_{d_i}\) and the position of the \((i+1)\)-th drive coil is \(x_{d_{i+1}}\),
\[
M_{d_{i+1},p}(x) = M_{d_i,p}(x - (x_{d_{i+1}} - x_{d_i}))
\]

4. Simulation and analysis of EMPS

4.1. Simulation parameters set-up

The simulation parameters are shown in Table 1 and Table 2.

**Table 1. Parameters of the coils.**

| Coil Type  | Material | Outside Diameter(m) | Inside Diameter(m) | Axial Length(m) | Number of Turns |
|------------|----------|---------------------|--------------------|-----------------|----------------|
| Drive Coil | Copper   | 5.5                 | 4.5                | 2               | 1000           |
| Armature Coil | Copper | 4.4                 | 3.5                | 2               | 1000           |
4.2. Mutual inductance simulation of armature and drive coil

It can be seen from equation (18) that the magnitude of the electromagnetic force is related to the current in the armature and the drive coil, and the mutual inductance between the armature and the drive coil. The former is related to the discharge process of the discharge circuit. In the discharge circuit, the other circuit parameters other than the mutual inductance can be considered as constant. If the armature and the driving coil are coaxial, the mutual inductance is due to the axial relative position variety. So in the entire simulation process, how to accurately get mutual inductance is essential.

| Track Length (km) | Series number | Weight of armature and vehicle(ton) |
|-------------------|---------------|------------------------------------|
| 6                 | 3000          | 350                                |

**Table 2.** Parameters of the track and the vehicle.

**Figure 3.** Brief description of configuration of coil launch system.

**Figure 4.** Side view of coil launch system.

The parameters of the coils have been shown in table 1 and table 2. Based on these parameters, Maxwell finite element model was established as figure 3 and figure 4 and analysis method is performed to analyze the mutual inductance of the armature and the drive coil in different positions.

The simulation results of the electromagnetic launch are shown in Figure 5 to Figure 8. Figure 5 to Figure 7 is the simulation results of the single stage EML. Figure 5 shows the maximum thrust of the single stage device reaches 1500 kN, reaches the peak at 1 second, and then decreases gradually until it is close to zero at nearly 2 second. The armature acceleration coincides with the armature thrust curve, which makes the single-stage acceleration process reach a stable high value at 2 second as it shows in Figure 6. After this time point, the electromagnetic thrust is small and is not sufficient for the armature acceleration, and because of the existence of inertia, armature continuingly performs uniform motion, which can be seen from Figure 7.

As it shows in Figure 8, the acceleration of the assembly in the whole multi-stage launch is gradually decreasing. This is due to the increase in the speed of movement of the assembly, so the effective acceleration effect of each the drive coil on the armature is decreasing.

5. Conclusion

Based on the principle of coil electromagnetic propelling, the equivalent current loop model is constructed and the mutual inductance and static magnetic field between the driving coil and the armature coil are simulated by Maxwell finite element analysis software. Combining with the model and simulation Data, the calculation of the electromagnetic propulsion can accelerate the spacecraft weight 133.3 tons to a velocity of 207 meters per second. Given that the weight of typical reusable vehicle is hundreds of tons, EMPS is doable to propel such spacecraft.
Figure 5. Electromagnetic forces applied to armature in z-direction.

Figure 6. Acceleration of armature.

Figure 7. Velocity of armature.

Figure 8. Acceleration of multi-stage electromagnetic launch.

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