Research on TBCC-RR Reusable Vehicle Launch System Based on Electromagnetic Propulsion

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Abstract. The traditional non-reusable launch vehicle is the main approach to complete space launch mission. But the traditional rocket is inefficient and uneconomical, the more economical space launch approach has been studied in recent years. Two-Stage-To-Orbit (TSTO) reusable launch configuration which is combined Turbine Based Combined Cycle (TBCC) with reusable rocket (RR) is one of the main trends of current research. Based on TBCC-RR approach, a new design was proposed to improve the carrying capacity. In this design, the electromagnetic propulsion system (EMPS) was applied to increase the initial speed as the first stage engine, leaving the TBCC-RR to take care of the rest launch job. The overall concept of To-Orbit system was constructed and the electromagnetic launch system model was established. Then the mathematic model of EMPS-TBCC-RR-To-Orbit system 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, using EMPS can reduce the takeoff weight of the spacecraft and significantly enhance the carrying capacity of the spacecraft. Therefore, it is foreseeable that EMPS has a certain potential in the future space launch mission.

1. Introduction

Nowadays the most mature aerospace launch approach is still traditional one-time launch rocket. But the traditional rocket has a significant weakness which is that the ratio of the payload to the total takeoff weight is quite small[1]. In the case of a Low-Earth Orbit (LEO) mission, the ratio is usually only a few percent, while the ratio become lower, even less than one percent in the geostationary orbit (GTO) task. Therefore, transporting a kilogram of load into the LEO need to spend four thousand to twenty thousand dollars[2]. Meantime the traditional rocket releases harmful exhausts which will pollute the atmosphere in the combustion process. Many scholars have been committed to finding a low-cost space launch technology, proposing 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. The electromagnetic propulsion system is one of the feasible concepts[5].

Electromagnetic launch technology recently fast developed. BaliKci A. and Zabar Z. [6] studied the possibility to launch missiles with large weight using electromagnetic force. Li Weibo and Cao Yanjie[7] established the simulation model of missile electromagnetic launch system. The United States Lake Hacker Naval Air Force Engineering Station successfully launched the T-45 Goshawk
Trainer[8], 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. So it is feasible to launch spacecraft with the application of electromagnetic propulsion technology.

2. Overall concept of EMPS-TBCC-RR Launch System

One of mainstream plan for reusable launch vehicle is combined TBCC with RR, while TBCC is configured to first stage, the second stage uses reusable rocket (RR). In this paper, we add a electromagnetic launch system in TBCC-RR configuration. The TBCC engine refers to Heppenheimer[8], the first-stage structure refers to the German TSTO concept Sanger[10], the second-stage spacecraft structure reference to the US X-33.

Inspired by the reference[11], we divided TSTO task into different nodes according to series and modalities of the engine, recorded these nodes as \( (V_i, H_i) (i = 1, 2, \ldots, N) \), where \( V_i \) and \( H_i \) represents the velocity and height of each flight node respectively. Define the flight mode of the \( i \) to \( i+1 \) node as the \( i \) mode, then the weight of the \( i \) node spacecraft is \( m_i \), the weight ratio of the \( i \) mode is \( \mu_i = m_i / m_{i+1} \).

Considering TSTO system consists of two stages, let the takeoff weight be \( m_b \) and \( m_o \) respectively. Where \( m_b \) includes propellant weight \( m_{bp} \) and structural equipment weight \( m_{bs} \), \( m_o \) including propellant weight \( m_{op} \) and structural equipment weight \( m_{os} \). Given the separation point \((V_s, H_s) (1 < s < N)\), after determining the mission profile, weight ratio of each mode can be calculated, thereby obtaining the total weight ratio of the first and the second stage, which is \( \mu_b \) and \( \mu_o \).

\[
\frac{m_{bp} + m_{bs} + m_{op} + m_{os} + m_i}{m_{bp} + m_{bs} + m_{op} + m_{os} + m_j} = \mu_b = \prod_{i=1}^{N} \mu_i
\]

\[
\frac{m_{op} + m_{os} + m_i}{m_{op} + m_{os} + m_j} = \mu_o = \prod_{s=1}^{N-1} \mu_i
\]

Where,

\[
\mu_i = \begin{cases} 
\frac{\exp((V_i - V_s^2)/2 + g(H_i - H_s))}{\eta q(1 - D/T)} & \text{suction engine} \\
\frac{\exp(V_i - V_s + 2g(H_i - H_s)/(V_s + V_o))}{g l_{op}} & \text{rocket engine}
\end{cases}
\]

Suppose that \( \frac{m_{bp}}{m_{bp} + m_{op}} = \sigma_b \), \( \frac{m_{os}}{m_{op} + m_{os}} = \sigma_o \). For a given payload \( m_i \), considering the formula above the total weight of the spacecraft taking off can be obtained by equation \( (3) \).

\[
m_{to} = m_{bp} + m_{bs} + m_{op} + m_{os} + m_i = \frac{(1 - \sigma_b)(1 - \sigma_o)\mu_b \mu_o}{(1 - \sigma_b)\mu_o}(1 - \sigma_o)\mu_o)
\]
Generally the initial launch state is $V_i = 0$, $H_i = 0$. So if we use accelerometer to increase the initial speed $V_i$, the total weight will be reduced. So a new approach to launch spacecraft to the given orbit was presented. We use electromagnetic propulsion system to accelerate TBCC-RR vehicle. The launch system consists of two parts, one is the spacecraft, the second is electromagnetic propulsion system. The work process and structure are shown in Figure 1.

3. 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.

![Figure 1. Overall concept of TBCC-RR vehicle orbit system.](image1)

![Figure 2. Schematic diagram of the equivalent current loop method.](image2)
trigger the discharge. Since the trigger switches of $i+1, i+2, \cdots, n$ 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,

$$u_i(t) = u_i(0) - \frac{1}{C_i} \int_0^t i_{\text{in}}(\tau) d\tau \quad (k = 1, 2, \cdots, i), \quad i_{\text{in}} = 0 \quad (k = i+1, i+2, \cdots, n)$$

(4)

According to Kirchhoff’s law of voltage, the mathematical model can be expressed as:

First stage

$$L_{i1} \frac{di_{1}}{dt} + L_{i1} \frac{di_{i1}}{dt} - \frac{d(M_{i1,L_1}i_1)}{dt} = u_i \quad (l \neq 1)$$

(5)

Second stage

$$L_{i2} \frac{di_{2}}{dt} + L_{i2} \frac{di_{i2}}{dt} - \frac{d(M_{i2,L_2}i_2)}{dt} = u_{i2} \quad (l \neq 2)$$

(6)

$$i\text{-th stage} \quad L_{i} \frac{di_{i}}{dt} + L_{i} \frac{di_{i}}{dt} - \frac{d(M_{i,L_i}i_{i})}{dt} = u_{i} \quad (l \neq i)$$

(7)

$$n\text{-th stage} \quad \frac{di_{n}}{dt} = 0 \quad (l \neq n)$$

(8)

Armature

$$R_{i} \frac{di_{p}}{dt} + L_{p} \frac{di_{p}}{dt} - \sum_{j=1}^{i} \frac{d(M_{j,p,i,j})}{dt} = 0$$

(9)

$$\frac{d(M_{i,p,i_{j}})}{dt} = \frac{dM_{i,p,i_{j}}}{dt} + M_{i,p,i_{j}} \frac{dv_p}{dx} + M_{i,p,i_{j}} \frac{dv_p}{dx}$$

(10)

The formulas (5) to (10) are arranged in a matrix form,

$$[R][I] + [L][\dot{I}] - [M][I] \dot{v}_p \frac{dM_{I}}{dx} [I] = [U]$$

(11)

among them,

$$[R] = \begin{bmatrix} R_{1} & R_{i1} & \cdots & R_{ip} \\ R_{i1} & L_{i1} & \cdots & R_{ip} \\ \vdots & \vdots & \ddots & \vdots \\ R_{ip} & R_{ip} & \cdots & L_{ip} \end{bmatrix}, \quad [L] = \begin{bmatrix} L_{i1} \\ \vdots \\ L_{ip} \end{bmatrix}, \quad [M] = \begin{bmatrix} \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ C_{i} & C_{i} & \cdots & C_{i} \end{bmatrix}, \quad [I] = \begin{bmatrix} I_{i1} \\ I_{i2} \\ \vdots \\ I_{ip} \end{bmatrix}, \quad \dot{[I]} = \begin{bmatrix} \dot{I}_{i1} \\ \dot{I}_{i2} \\ \vdots \\ \dot{I}_{ip} \end{bmatrix}$$

$$[M_{i}] = \begin{bmatrix} 0 & M_{i,p} & \cdots & M_{ip} \\ M_{i,p} & 0 & \cdots & M_{ip} \\ \vdots & \vdots & \ddots & \vdots \\ M_{ip} & M_{ip} & \cdots & 0 \end{bmatrix}, \quad [U] = \begin{bmatrix} u_{i1} \\ u_{i2} \\ \vdots \\ u_{ip} \end{bmatrix}, \quad \frac{dM_{i}}{dx} = \begin{bmatrix} 0 & \frac{dM_{i,p}}{dx} & \cdots & \frac{dM_{ip}}{dx} \\ \frac{dM_{i,p}}{dx} & 0 & \cdots & \frac{dM_{ip}}{dx} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{dM_{ip}}{dx} & \frac{dM_{ip}}{dx} & \cdots & 0 \end{bmatrix}$$

Let the time step be $\Delta t$, then the time series will be $t_n(n = 0, 1, 2, \cdots)$, so the current derivative at $t_{n-1}$ is:

$$\dot{[I]}_{n-1} = ([L]_{n-1} - [M_{i}]_{n-1})^{-1} \left( [U]_{n-1} + v_{p(n-1)}(\frac{dM_{i}}{dx})_{n-1} - [R][I]_{n-1} \right)$$

(12)

The axial electromagnetic force $F_n$ received by the armature at $t_n$ can be expressed as:

$$F_n = \sum_{i=1}^{n} (\frac{dM_{i,p}}{dx})_i I_{i1} I_{p}$$

(13)

Where, $(\frac{dM_{i,p}}{dx})_i$ is the interaction gradient between the drive coil of a stage $i$ and the armature at
t_n; \ i_{\text{dia}} \) is the current of the stage I drive coil at \ t_n; \ i_{\text{pm}} \) is the momentary current of the armature at \ t_n. 

The armature motion can be expressed as:

\[
a_n = \frac{F_n}{m}, \quad v_n = a_{n-1}\Delta t + v_{n-1}, x_n = x_{n-1} + v_{n-1}\Delta t
\]  

Where, \ a_n \) is the acceleration of the armature, \ v_n \) is the speed of the armature, \ x_n \) is the displacement of the armature.

![Figure 3. TBCC-RR vehicle mission profile](image)

4. Simulation and analysis of EMPS-TBCC-RR launch system

4.1. Orbit mission simulation
In order to reach the maximum efficiency of the TBCC engine, the vehicle needs to maximize the use of oxygen in the air in the working section of the TBCC engine, so that the vehicle's flight path is stable in this section, mainly in the lower altitude perform accelerated motion, and then relies on RR for height Climb up. The mission profile for this phase of the vehicle is shown in Figure 3. The EMPS-TBCC-RR launch system design parameters are shown in Table 1.

| TBCC-RR concept | EML concept |
|-----------------|-------------|
| Payload(t)      | 8.0         | Coil material | Copper |
| Track height(km)| 200         | Diameter (m)  | 4.5    |
| Stamp open height (km) | 15         | Outside diameter (m) | 5.5 |
| Burning open Ma | 6           | Drive Coil    |       |
| Flame open height (km) | 22.5     | Axial length(m) | 2     |
| Turbo mode q (J/kg) | 4.2e7     | Number of turns | 1000 |
| Turbo mode \( \eta \) | 0.4       |             |       |
| Turbo mode T/D  | 3           | Armature Coil |       |
| Sub/Scrambling mode q (J/kg) | 5e7 | Axial length(m) | 2     |
Sub/Scrambling mode
\[ \eta \]
- \[ \eta \] = 0.4

Number of turns 1000

Sub/Scrambling mode
T/D
- T/D = 3.5

Track length 6km

Second stage rocket
\[ I_s (\text{s}^{-1}) \]
- \[ I_s \] = 450

Series number 3000

\[ \sigma_b \]
- \[ \sigma_b \] = 0.614

Weight of armature and vehicle (t) 800

\[ \sigma_v \]
- \[ \sigma_v \] = 0.238

4.2. Simulation Result

The parameters of the coils have been shown in Table 1. The simulation results of the electromagnetic launch are shown in Figure 4–5. The armature acceleration coincides with the armature thrust curve, which makes the single-stage acceleration process reach a stable high value at 0.5 seconds as it shows in figure 4. After this time point, the electromagnetic thrust is small and is not sufficient for the armature acceleration. As it shows in Figure 5, 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.

| Power supply voltage (kV) | No accelerate | 100  | 200  | 300  | 400  |
|---------------------------|---------------|------|------|------|------|
| Takeoff speed (m/s)       | 0             | 79.8 | 140.81 | 194.2 | 207.5 |
| Takeoff weight(t)         | 347.8         | 347.1 | 345.6 | 343.8 | 343.2 |

Figure 4. Acceleration of armature.

Figure 5. Acceleration of multi-stage electromagnetic launch.

If no electromagnetic propelling, takeoff weight of the spacecraft will be 347.8 t. In the case of electromagnetic propelling, the takeoff weight is reduced. When the other parameters of the system remain constant, only when the power supply voltage is increased, the takeoff speed of the vehicle will be increased as shown in Table 2. However, as the voltage gradually increases, the trend of the increase of take-off speed has obviously slowed down. As the initial velocity increases, compared with the traditional way, the spacecraft takeoff weight reduces from 347.8t to 343.2 t when it carries same payload into the orbit, and compared to 8t task load, the weight is also impressive.

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. In the simulation, the calculation of the design electromagnetic propulsion

can accelerate the spacecraft weight 343.2t to 207m/s. The result shows that the EMPS-RBCC_RR launch system can reduce the takeoff weight of the spacecraft and significantly enhance the carrying capacity of the spacecraft.

Acknowledgments
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