Modeling and Simulation of Air-Vehicle Entry Scheme Based on Composite Precooling Engine

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Abstract. Based on the composite precooling engine, a Single-Stage-To-Orbit (SSTO) scheme is proposed. The climbing process is divided into three stages. The dynamic model, the air-vehicle model and the motion model are set up, and the feasibility of SSTO is studied using the numerical simulation. In order to improve the SSTO scheme, a SSTO scheme based on launching vehicle is proposed and a Two-Stage-To-Orbit (TSTO) powered by the composite precooling engine in the first stage and the rocket engine in the second stage is proposed. The results show that if the SSTO scheme is achieved, the structural coefficient of the air-vehicle should be less than 0.13, which has great technical difficulty. By adopting the SSTO scheme based on launching vehicle, the structural coefficient can be relaxed to 0.19, and the technical difficulty will be greatly reduced. The adoption of the TSTO scheme can not only effectively reduce the technical difficulty, but also increase the payload from 15t to 20.31t.

Introduction

In recent years, the aerospace powers led by the United States and Russia have proposed and are implementing a series of design and development plans for combined cycle engines [1]. A combined cycle engine refers to the combination of two or more traditional power plants, which can be complementing the advantages of different engines by organic bond of structures and parts [2]. The composite precooling engine is a common combined cycle engine, in which the Synergistic Air-Breathing Rocket Engine (SABRE) proposed by Reaction Engine Ltd (REL) is the typical representative [3].

The SABRE engine is a combined cycle engine that uses a unique thermal cycle to transfer and convert the energy between the high temperature air and the low temperature hydrogen. It can operate in the full space and full speed range. It has the Air-Breathing Mode and the Rocket Mode, when in the dense atmosphere (Mach 5 & 25 km) the engine works in the Air-Breathing Mode, otherwise it works in the Rocket Mode. SABRE engine has attracted wide attention since it was put forward. The concept of composite precooling engine and the structure of SABRE engine are introduced in reference[4]. The development status of SABRE engine is summarized and the future research is prospected in reference[5]. The SABRE engine system scheme is analyzed in reference[6]. It is considered that the SABRE engine has obvious performance advantages and is expected to be a new power device for the reusable SSTO vehicle. The thermodynamic cycle scheme of SABRE engine is studied in reference[7]. It shows that the Air-Breathing Mode adopts the Brayton thermodynamic cycle and the Rocket Mode adopts the rocket engine thermodynamic cycle. The research status of SABRE engine pre-cooler is summarized in reference[8]. It is considered that the pre-cooler technology is one of the key technologies of the composite precooling engine. The key technical parameters of the SABRE engine pre-cooler are calculated in reference[9] and the overall parameters of the pre-cooler are estimated. Reference[10] announced the future development plan of SABRE engine. It is expected that 2025~2030 will be the first time to carry out engine application flight test. It can be seen that there is much research on the SABRE engine system scheme and key technology both home and abroad, but the research on the air-vehicle entry scheme based on the SABRE engine is
little. In the public references, only in 2016, the United States announced the TSTO scheme based on
the SABRE engine on the AIAA conference\textsuperscript{[11]}

Based on the composite precooling engine, a SSTO scheme is proposed. The dynamic model,
air-vehicle model and motion model are established. The feasibility of the composite precooled
engine as a SSTO vehicle power device is verified. On this basis, the improvement of SSTO scheme
is improved, and the SSTO scheme based on launching vehicle and TSTO scheme are proposed, and
the technical difficulty is simulated and analyzed. The results can provide reference for the
application research of the composite precooling engine.

Model Construction

Overview of SSTO Scheme

The air-vehicle carries the payload to the 300km orbit by means of horizontal take-off and landing.
The lifting process of air-vehicle is divided into three stages: Horizontal Take-off Stage,
Air-Breathing Mode Climbing Stage and Rocket Mode Climbing Stage. The air-vehicle leaves
the ground at a speed of about Mach 0.5 and climbs to the height of about 25km in Air-Breathing Mode,
after which, the engine switches to the Rocket Mode. Rocket Mode Climbing Section is divided into
two stages, one is the First Stage of Rocket Mode and the other one is the Second Stage of Rocket
Mode. The First Stage of Rocket Mode is below 100km, considering the effect of engine thrust,
gravity and aerodynamic force. The Second Stage of Rocket Mode is 100km-300km, considering the
effect of engine thrust and the gravity of vehicle. At the end of the trajectory, the air-vehicle turns into
300km's low earth orbit under the effect of gravity. After the completion of the task, the air-vehicle
slides to the ground to achieve reuse in the absence of power.

The Dynamic Model

The air-vehicle is powered by two SABRE engines, but the detailed information about the thrust of
the SABRE engine is not found in the public data. In order to establish the dynamic model, the thrust
of the SABRE engine is required to be calculated.

The flow of gas in the nozzle can be considered as an adiabatic equilibrium flow. The gas in the
expansion process does not change. The import loss, the loss of friction, the loss of expansion and the
loss caused by the boundary layer are ignored. The thrust of the SABRE engine can be obtained
according to the Eq. 1. The thermal calculation is carried out by NASA Chemical Equilibrium with
Application (CEA). The flow of air and liquid hydrogen through the SABRE engine is given by the
reference\textsuperscript{[12]}. The physical properties of the fluid refer to the US National Institute of Standards and
Technology(NIST) database. The flight environment of the engine is given by the reference\textsuperscript{[13]}, and
the air model uses the 1976 standard gas model of the United States. When the ambient pressure is
much higher than the designed pressure of the nozzle gas outlet, the airflow will be separated in the
nozzle. The calculation process can be referred to reference\textsuperscript{[14]}. The equation for calculating the
thrust of the engine is as follows:

\begin{equation}
F = \begin{cases} 
    m v_e + (P_e - P_{amb}) A_e & P_e \geq 0.215 P_{amb} \\
    m v_{sep} + (P_{sep} - P_{amb}) A_{sep} + \xi_{sep} (P_{sep} - P_{amb}) (A_e - A_{sep}) & P_e \leq 0.215 P_{amb}
\end{cases} 
\end{equation}

In the equation: \( m \) represents gas outlet flow of nozzle; \( v_e \) represents gas outlet speed of nozzle;
\( P_e \) represents gas outlet pressure of nozzle; \( P_{amb} \) represents the ambient pressure of engine;
\( A_e \) represents nozzle exit cross-sectional areas; \( v_{sep} \) represents the speed at gas separation section;
\( P_{sep} \) represents the pressure at gas separation section; \( \xi_{sep} \) represents recovery coefficient of pressure,
which is between 0.1 and 0.5.
The results of the calculation are shown in Fig. 1. It can be seen from the graph that the results in this paper are in good agreement with those published by REL, and the maximum error is 4.8%, which shows the accuracy of the results.

![Figure 1. The variation of SABRE engine thrust as a function of height.](image)

**The Air-Vehicle MODEL**

The take-off quality of the air-vehicle is 345t and the payload is 15t. In reference[15], the concept of reusable SSTO vehicle is constructed and introduced. The configuration of the air-vehicle is given. The aerodynamic parameters of the air-vehicle are obtained by combining the CFD method with the engineering estimation method. As shown in Fig. 2, the maximum lift-drag ratio is 9 under subsonic state. The maximum lift-drag ratio is 5 under the state of Mach 2, which is lower than the maximum lift-drag ratio of Concorde supersonic airliner(the maximum lift-drag ratio of Concorde supersonic airliner under the state of Mach 2 is 7). Therefore, we can think that the aerodynamic parameters of the air-vehicle are correct at the theoretical level and can be used as the aerodynamic model of the air-vehicle in the SSTO scheme.

![Figure 2. The aerodynamic model of air-vehicle.](image)

**The Motion Model**

**The Horizontal Take-Off Stage.** At the horizontal take-off stage, air-vehicle is affected by gravity, aerodynamic force and ground friction resistance. The air-vehicle accelerates horizontally under the net force. The equations of motion are as follows:
\[
\frac{dv}{dt} = \frac{T - D - F}{m}
\]
\[
D = \frac{1}{2} \rho v^2 \cdot S \cdot C_D
\]
\[
F = f(W - L)
\]
\[
W = mg
\]
\[
L = \frac{1}{2} \rho v^2 \cdot S \cdot C_L
\]
\[
\dot{m} = m_0 - \dot{m} t
\]
\[
\frac{dx}{dt} = v
\]

In the equation: \(v\) represents the speed of air-vehicle; \(T\) represents the thrust of engines; \(D\) represents the aerodynamic drag; \(F\) represents the ground friction resistance; \(m\) represents the mass of air-vehicle; \(m_0\) represents the Initial mass of air-vehicle; \(\dot{m}\) represents the fuel consumption rate; \(\rho\) represents the density of air; \(S\) represents the characteristic area of air-vehicle; \(C_D\) represents the drag coefficient of air-vehicle; \(C_L\) represents the lift coefficient of air-vehicle; \(f\) represents the ground friction resistance coefficient; \(W\) represents the gravity of air-vehicle; \(x\) represents the horizontal displacement of air-vehicle.

The value of each quantity is shown in Tab.1.

| physical quantity | \(T\) (kN) | \(C_L\) | \(C_D\) | \(S\) (m²) | \(\dot{m}\) (kg) | \(\rho\) (kg·m⁻³) | \(f\) | \(m_0\) (t) |
|------------------|-------------|---------|---------|-----------|--------------|-------------------|-----|-----------|
| value            | 762.85×2    | 0.4376  | 0.0486  | 379       | 62           | 1.225             | 0.035| 345       |

The Air-Breathing Mode Climbing Stage. As shown in Fig. 3, at this stage, the air-vehicle leaves the ground at a fixed angle \(\theta\). The air-vehicle climbs up to about 25km under the effect of gravity and aerodynamic forces, the SABRE engine works in Air-Breathing Mode.

The equations of motion are as follows:

\[
\begin{align*}
ma_x &= T \cos \theta - L \sin \theta - D \cos \theta \\
ma_y &= T \sin \theta + L \cos \theta - D \sin \theta - W
\end{align*}
\]  

In the equation: \(a_x\) represents the horizontal acceleration of air-vehicle; \(a_y\) represents vertical acceleration of air-vehicle; \(\theta\) represents the angle of attack.

Using \(a \cos \theta\) and \(a \sin \theta\) to replace \(a_x\) and \(a_y\) respectively, the Eq. 3 can be simplified as follows:
\[ a = g \left( \frac{T}{W} - \frac{\cos \theta}{K} - \sin \theta \right) \]  

In the equation, \( a = \frac{dv}{dt} \); \( g = g_0 \left( \frac{R}{K + H} \right)^2 \) (\( g_0 \) represents the ground surface acceleration, \( R \) represents the radius of earth, \( H \) represents the height of air-vehicle); \( W = (m_t - \dot{m} t) g ; \)
\( K = \frac{L}{D} \) represents the lift-drag ratio of air-vehicle.

According to Eq. 4, the differential equation of motion of Air-Breathing Mode Climbing Stage is as follows:

\[ \frac{dv}{dt} = \frac{T}{m_t - \dot{m} t} - g_0 \left( \frac{R}{R + H} \right)^2 \frac{\cos \theta}{K} - g_0 \left( \frac{R}{R + H} \right)^2 \sin \theta \]  

*(Rocket Mode Climbing Stage)*. With the altitude increasing, the air density decreases. When the air flow can’t meet the demand of SABRE engine, it switches to the Rocket Mode. When the height of flight is higher than the design height of nozzle, the specific impulse will remain for the vacuum specific impulse and the value of specific impulse will not change\(^{16}\). The Rocket Mode works above 25km, so the specific impulse is a constant, the value of vacuum specific impulse of hydrogen-oxygen rocket is 4500m/s. The thrust can be controlled by adjusting the fuel flow.

In the First Stage of Rocket Mode, the air-vehicle continues to climb at a fixed angle \( \theta \), the force analysis and motion equation is same to that in Air-Breathing Mode Climbing Stage.

The equations of motion in the Second Stage of Rocket Mode are as follows:

\[ \begin{align*}
    \frac{dv}{dt} &= T - W \\
    T &= \dot{m} \cdot \text{Isp} \\
    W &= mg \\
    m &= m_2 - \dot{m} t
\]  

In the equation: the gravity acceleration can refer to the United States 1976 standard atmospheric model; \( m_2 \) represents the initial mass in the Second Stage of Rocket Mode Climbing Stage; \( \dot{m} \) represents the fuel consumption rate, which is 6.04.

**Model Hypothesis**

1. The air-vehicle takes off near the earth’s equator, regardless of the influence of earth curvature and rotation, and the earth is seen as a sphere with homogeneous density.
2. Regardless of the change of centroid and center of pressure during the flight, and Regardless of the rolling and yaw of the air-vehicle.
3. Neglecting the influence of atmospheric disturbance on the flight process

**Results and Analyses**

**The Simulation Results**

Four order Runge-Kutta Method is used to solve the equations of motion of each stage, and the results are shown in Fig. 4~7. From the Fig. 4, we can find that the acceleration of a vehicle in a dense atmosphere is small, and its maximum acceleration is only 21m/s\(^2\), in order to reduce the work to overcome air resistance. When the air-vehicle leaves the atmosphere, the acceleration increases rapidly. From the Fig. 5, we can find that the maximum speed is 7925m/s. From the Fig. 6, we can find that the horizontal displacement of the aircraft during the whole rising process is 1100km, and it can be seen that the aircraft carried out a long distance flight in the atmosphere in order to make better
use of the aerodynamic lift. From the Fig. 7, we can find that the air-vehicle can reach the height of 300km.

To sum up, when the aircraft arrived at the earth orbit of 300km, the speed is 7925m/s, which meets the demand of speed to enter orbit (7700m/s), we can think that the SSTO scheme is feasible. The corresponding time for each flight stage is shown in Tab. 2, the total flight time is 768s.
Table 2. The corresponding time for each stage.

| Incident                                      | Start Time(s) | End Time(s) |
|-----------------------------------------------|---------------|-------------|
| The Horizontal Take-off Stage                 | 0             | 46          |
| The Air-Breathing Mode Climbing Stage         | 47            | 431         |
| The First Stage of Rocket Mode                | 432           | 735         |
| The Second Stage of Rocket Mode               | 736           | 768         |
| Reach the Pre-Selected Orbit                 | 768           | -           |

The Analyses of Results

According to the working time and the engine propellant flow rate of each stage, the total consumed propellant can be obtained. The total quality of air-vehicle consists of structure quality, propellant quality and payload. If the propellant quality and payload are known, the structure quality of air-vehicle can be obtained. As a result, the structure quality coefficient can be obtained. The SSTO vehicle usually requires a low structure coefficient. It will be difficult to realize SSTO when the structure coefficient is high.

The total consumption of propellant can be calculated as follows:

\[
m_i = \int m \cdot dt \tag{7}
\]

In the equation: \( m_i \) represents the total consumption of propellant.

According to the Eq. 7, the total propellant consumed by air-vehicle is 286t, so the structure quality is 43t and the structure coefficient is 0.13. In today’s material and technical conditions, it is difficult to achieve so low coefficient\(^{[16]}\). Hence the SSTO scheme should be improved or TSTO scheme should be developed firstly for realizing easily.

Program Improvement

**SSTO Launch Vehicle Scheme.** When the aircraft takes off from the ground, the total quality of take-off is large and the need of strength of landing gear is high. The quality of the landing gear is large, which accounts for about 7% of the total take-off mass of the air-vehicle, resulting in a large structural coefficient.

If the launch vehicle (such as magnetic levitation train) is used to accelerate the air-vehicle at take-off stage, the mass of landing gear can be reduced by 80%, moreover, propellant is no longer needed in take-off stage. In this paper, the take-off mass of air-vehicle is 345t, when using the SSTO Launch Vehicle Scheme, the mass of landing gear can be reduced by 19.32t and the propellant can be reduced by 2.85t. In other words, the total take-off mass can be reduced by 22.17t. At this time, if the structure coefficient is designed as 0.13, it is equivalent to 0.19 of the structure coefficient of the aircraft that takes off in the horizontal skating mode, which will greatly reduce the technical difficulty.

**The TSTO Scheme.** Reusable SSTO vehicles can greatly reduce the launch cost, but it is very difficult to achieve. The main reason is that a large quantity of structural mass is brought into space. The technology of the Multistage Stage To Orbit scheme is always relatively easy, but the cost of launch is high. Take both the difficulty of technology and the cost of launching into consideration, the TSSO scheme should be given priority to develop.

1. **Overview of TSTO scheme.** The total take-off mass is 345t, two SABRE engines are used in the first stage, the structure coefficient is 0.19. The rocket engine is used in the second stage, the structure is simple, the structure coefficient is 0.12. The SABRE engines propel the air-vehicle on the ground to take off and climb to the height of 25km in Air-Breathing Mode, and then it switches to the Rocket Mode. At the height of 100km, the second stage separates from the first stage. The second level
continues to carry the payload to reach the near-earth orbit of 300km, and the first stage glide back to the ground.

2. The Analysis of the TSTO Scheme. The first stage can be divided into three stages: the Horizontal Take-Off Stage, the Air-Breathing Mode Stage and the Rocket Mode Stage, the equations of motion are same to that in SSTO scheme. The equations in TSTO scheme are same to that in the second stage of Rocket Mode in SSTO scheme. According to the simulation calculation, it can be obtained that the propellant consumed in the first stage of TSTO air-vehicle is 224.36t, so the initial mass of the Second Stage of TSTO air-vehicle is 55.04t. When the second stage reaches the height of 300km, the velocity is 7910m/s, which meets the demand. The propellant consumed in the second stage is 28.13t, so the payload is 20.31t. The mission profile of the TSTO Scheme is shown in Fig. 8.

![Figure 8. The variation of vertical displacement with time in TSTO scheme.](image)

Compared with SSTO scheme, TSTO scheme is easier to realize. When the take-off mass is the same, the payload can be increased by 5.31t, which can decrease the launch cost. Compare with Britain REL “SKYLON”, the payload coefficient rises from 3.74% to 5.89%, it has a big advantage.

Summary

Based on the composite precooling engine, the approach to the orbit of the air-vehicle is studied. A SSTO scheme is proposed, the equations of motion are established in each stage and the numerical simulation calculation is carried out. The feasibility and technical difficulty are analyzed. The SSTO scheme is improved, besides, the SSTO Launch Vehicle Scheme and TSTO scheme is proposed. The main conclusions are as follows:

1. In the SSTO scheme, when the air-vehicle reaches the height of 300km, the total time is 768s, and the velocity is 7925m/s, which meets the demands. The SSTO scheme is feasible, but the structure coefficient is limited to 0.13, which is difficulty under the current material and technical conditions

2. In the SSTO Launch Vehicle Scheme, the structure mass can be reduced by 19.32t, the propellant mass can be reduced by 2.85t, the structure coefficient of the air-vehicle can reach 0.19. It is easier than the SSTO scheme.

3. In the TSTO scheme, the SABRE engine is used in the first stage, and the rocket engine is used in the second stage. Compared with SSTO scheme, the TSTO scheme is not only easy to realize, but also the payload can increases from 15t to 20.31t, which the launch cost is decreased effectively.

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