Research Progress of Key Technologies for Typical Reusable Launcher Vehicles

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Abstract. In recent years, driven by space X and other commercial companies, the requirement of low cost and fast response to transport, reusable launch vehicle technology is attracting the world's attention. Aerospace agencies in various countries have stepped up research and made some progress in the related technologies of reusable launch vehicles. The development of reusable launch vehicle has become an important direction of space development in the future. First, the development status of reusable vehicles, the Space Shuttle Mode, the Falcon-9 Mode, the Launch Mode on board, and the Airborne Aircraft Mode, are introduced. Second, the structure design, the propulsion system, the recycling scheme, the thermal protection system and the launch costs of each mode is analyzed. Third, some related development suggestions are put forward in terms of the carrier configuration, the design of recycling scheme, the choose of propulsion system and the thermal protection system for reusable launch vehicle designer.

1. Introduction

With the development of Space Vehicles, people's activities extend to space. At present, multi-stage disposable launch vehicle is still the main mode of delivery. Although multi-stage launch vehicle is a reliable way, the high launch cost greatly restricts the development of civil, commercial and military activities in space. Since the 1960s, space agencies have tried to design a fully reusable vehicle to reduce launch costs and increase launch frequencies. Reusable launch vehicle is an effective way to reduce the cost of space transportation system. from the space shuttle to x series testing machines to the falcon - 9 launch vehicle, which has been developing rapidly in recent years, reusable launch vehicle is an important step to capture the commanding heights of space in the future.

In recent years, with the increasing importance of space and the rise of commercial spaceflight, there has been more interest in finding new ways to recycle vehicles to reduce costs. Table 1 shows the current research progress of typical reusable launcher vehicles.

Therefore, by analyzing the current development of various reusable launch vehicles, we can provide references for the development of reusable launch vehicles in our country. According to the different reusable methods, the development of reusable launch vehicle is divided into the space shuttle mode, the falcon-9 mode, the launch mode and the space plane mode. Four modes are further analyzed from aspects of the structural design, the propulsion system, the launch return design, the thermal protection system and the launch and development cost.
Table 1. Research Progress of Reusable Launcher Vehicles

| Type                     | Model   | Research Progress                        |
|--------------------------|---------|------------------------------------------|
| Parachute Recovering     | Saturn I| Complete the subscale test               |
|                          | SRB     | Engineering application                  |
|                          | Energy boosters | Propose a concept                      |
|                          | K-I Rocket | Complete the imitative start            |
|                          | Sub-Mars  | Complete the flight test                 |
|                          | DC-X     | Complete the low altitude flight test    |
| Vertical return          | Charon  | Complete the low altitude flight test    |
|                          | New Shepard | Complete once reusable flight test      |
|                          | MOD      | Complete the vertical take-off and landing in different locations |
|                          | Falcon-9 | Complete the recycle multiple times, breakthrough the corresponding technologies |
| Winged return            | Baikal's booster | Propose a concept                  |
|                          | Adeline System | In the research                     |
|                          | XS-I     | Phase II flight test                    |
|                          | Leopard Cat | Complete a concept                     |
|                          | III      |                                           |
|                          | RLV-TD   | Complete the first-time flight test      |
|                          | X-37B    | Engineering application, multiple reused|
|                          | X-38     | Complete the imitative start            |
|                          | RLV-T1   | Complete the multiple hovering flight    |

2. Space Shuttle Mode

2.1 Structure Design
The space shuttle consists of three main components: an orbiter, an outer fuel tank, and two solid rocket boosters (SRB). The liquid propellant is installed in an independent external fuel storage tank, which does not occupy the space of the orbiter and effectively reduces the size and weight of the orbiter. The outer fuel storage tank burned down in the atmosphere after being separated, and the orbiter and two solid rocket boosters were recycled. The orbiter is divided into front, middle and rear sections. The middle section is the payload compartment, although it can carry up to 29 t of payload at a time, due to the wing, the payload ratio is relatively low. The rear section is equipped with three main engines, two orbital motor engines and a reaction control system. While meeting the power requirements, the rear section is also equipped with elevon, flap, vertical tail, rudder and speed brake. In the process of blindly pursuing the advanced nature of the system and the ability to adapt to various tasks, the space shuttle system has very complicated structure and low reliability. Many new structures are proposed in the space shuttle, such as the design of the tail wing, which provides a good reference for the next space shuttle.

2.2 Propulsion System
The main engine of the space shuttle is SSME (also called RS-25 in the company), as shown in figure 1, which is the largest phase combustion liquid hydrogen / liquid oxygen engine in the world at present. Each main engine provides about 1.8MN [1] thrust during take-off. The main engine and propellant parameters are shown in table 2.

During flight, SSME thrust can be adjusted from 67% to 109%, and the launch usually uses 104.5% thrust. Although adjustable thrust is achieved, some studies show that when engine thrust exceeds 104.5%, it has obvious influence on engine reliability [2]. Based on SSME, a new type of three-mode heat pipe jet engine (PRRDJE) is proposed, which makes full use of oxygen and hydrogen fuel in the atmosphere and has a fast combustion speed and can meet the thrust requirements of the
whole space flight [3]. Its simple structure and light weight are beneficial to the optimal pneumatic layout and good operation economy, and it can be an ideal engine for single-stage on-orbit and horizontal take-off and landing carriers.

![Figure 1. SSME engine](image)

| Table 2. SSME engine and propellant parameters |
|-----------------------------------------------|
| Parameter                   | Value             |
| Length                       | 4.3m              |
| Diameter                     | 2.4m              |
| Thrust                       | 2090kN/1670kN     |
| Specific Impulse             | 452s/366s         |
| Thrust-weight Ratio          | 73.1:1            |
| Cell Pressure                | 2747 psi          |
| Exit Pressure                | 1.049 psi         |
| Burning Time                 | 520s              |
| Propellant                   | Liquid Oxygen/ Liquid Hydrogen |
| Propellant Mixture Ratio     | 6.0               |

2.3 Recycling Scheme
The space shuttle recovery by taking off vertically and landing horizontally, SRB recovery adopts traditional parachute recovery; The orbiter of the space shuttle is landing horizontally and the external fuel tank is not recycled. The SRB's recovered parachutes and payloads are the largest. Each booster USES three main umbrellas to slow down and land at sea. Orbiter adopts the recovery method of horizontal landing, which is intended to be close to aircraft mode in operation, so as to shorten the time between two launches, and enable the recovery and reuse of the spacecraft's expensive equipment, so as to achieve the goal of fast, reliable and cheap. But because of the space shuttle’s design of return blindly pursue advanced and the adaptability of each task, its structure is too complex, maintenance costs rose sharply, it takes 14,000 standard hours to replace the surface heat shield alone, the ground operation costs accounted for 45% of the cost [4]. So, compared with the benefits of recycling, the benefits are not worth the loss. In addition, the complex structure leads to the reliability of the shuttle need to be improved.

2.4 Thermal Protection System
In high temperature (1260-1500 °C), mainly is the nosecone, the lower part of the fuselage and the leading edge of a wing which have Carbon/carbon composites and metal materials with good reusability. Carbon/carbon composites have excellent properties of high strength, high modulus and low density. However, Carbon/carbon composite materials do not have excellent thermal insulation performance, so it is necessary to fill the insulation between the outer shell and the body structure of the composite materials. The main metal material is refractory metal, which has the disadvantage of high density, such as Cobalt - and nickel-base high temperature alloys, tantalum, niobium and so on.

High temperature ceramic heat insulation tiles are generally used as heat protection materials on the nose and the lower surface of the fuselage, while low temperature ceramic heat insulation tiles are used on the side and vertical tail of the fuselage. The two kinds of heat insulation tile materials are the same, only there are differences in density, thickness and coating. The advantages of these two kinds of insulation tiles are small thermal expansion coefficient, low thermal conductivity, light weight and good thermal stability. However, due to the brittle ceramic materials and long maintenance period and high cost, they are easy to fall off and have the disadvantage of low reusability. Flexible heat insulation material is used on the upper surface of the fuselage with the temperature lower than 400 °C.
2.5 Development and launch costs
The United States has developed and launched five space shuttles, each of which has been spent $2 billion and has been launched over a hundred times, it costs $500 million every time, and each time it has to go back with a lot of manpower and resources to maintain and repair. In 1985-1988, the shuttle launch costs increased by 85%, to $90 million.

3 “Falcon-9” Mode
In the eighties of last century, McDonnell Douglas's dc-x test machine first proposed a vertical take-off and landing approach in order to develop a reusable vehicle that would be more reliable than the space shuttle and provide lower launch costs and faster responsiveness. The Charon and New Shepard of Blue Origin, the Mod of Armadillo Aerospace, the Xombie of Masten and the RLV-T3 Rocket of Link space in China all have tested the vertical take-off and landing scheme successively. In December 2015, SpaceX launched its Falcon-9 rocket has realized the launch and recovery of the inland landing field for the first time, reclaiming the carrier rocket's sub-stage on the premise of completing a satellite launch. Vertical take-off and landing aircraft developed by global commercial space corporation is shown in figure 2.

3.1 Structure Design

The reusable launch vehicle using reverse vertical take-off and landing basically adopts the traditional rocket configuration, which is simpler and easier to control than complex structures such as winged and lifting body. “Falcon-9” added four folded x-wing grills to the arrow body at one sub-stage for recovery steering and four landing buffers. The first stage of New Shepard is loaded with six footpads, and any failure of one of them can still ensure a successful landing. It uses a pneumatic rudder to slow down and has a small capacity to recover damage at sea [5].

3.2 Propulsion System
The first stage of “Falcon-9” selects 9 Merlin1D engines, including 1 central engine, and the remaining 8 engines are in a ring around the central engine, as shown in the figure 3 [6]. This structure simplifies the design and assembly of engine parts and simplifies the manufacturing process. The
Merlin 1D engine uses liquid oxygen/kerosene propellant. The main parameters are shown in the table 3. Compared with previous versions of Merlin series engines, the Merlin 1D can achieve throttling control from 100% to 70%. Later, the engine has been improved to work at a minimum of 40% full thrust. In addition, the basic mixing ratio of Merlin engine is controlled by the size of the supply pipeline, and a small amount of fuel flow is regulated by a throttle valve controlled by a brake, which can provide precise mixing ratio control, so as to realize the reverse thrust control of variable thrust vector in the process of return, with good throttling and stopping performance. In order to adapt to the full thrust range of Merlin 1D, the dense treatment of propellant is adopted to increase the mass of propellant.

Table 3. Merlin1D engine parameters [7]

| Parameter       | Value               |
|-----------------|---------------------|
| Length          | 4.3m                |
| Diameter        | 2.4m                |
| Thrust          | 2090kN/1670kN       |
| Specific Impulse| 452s/366s           |
| Thrust-weight Ratio | 73.1:1          |
| Cell Pressure   | 2747 psi            |
| Exit Pressure   | 1.049 psi           |
| Burning Time    | 520s                |
| Propellant      | LOX/RP-1            |
| Propellant Mixture Ratio | 6.0             |

3.3 Recycling Scheme
During the flight of “Falcon-9”, after the first and second stage separation of the rocket at an altitude of about 80km and the inertial impulse reaches the highest point, the flight attitude control is carried out by using the RCS control system, grid wings and so on, and finally the recovery of the land launch site is realized. Figure 4 shows the trajectory of the “Falcon-9” sub-class recovery flight [8].

When landing at the landing site, the primary center engine starts and decelerates to a landing speed of 2m per second. After 10 seconds of landing spray, the four landing supports were opened to complete the landing.

3.4 Thermal Protection System
“Falcon-9” shell and dome are made of aluminum and lithium alloy, with reliable welding technology to ensure the strength of 5 structures. The inter-stage is made of carbon fiber aluminum core composite structure, and the second and the first stages are made of high strength aluminum lithium alloy. In addition, the chief technology officer of Space X announced BLOCK 5 “Falcon-9” will be
launched at the end of 2017, which uses a more heat-resistant titanium grille and a new class of thermal protection coatings, and a reusable thermal protection material for rocket engines. A thermal protection layer is added at the end of the first stage to reduce the ablation of the shell and engine by backward thrust.

3.5 Launch Costs
The cost of the “Falcon-9” launch was $61.2 million. With only one sub-level recovery, the launch price can be reduced to $45.36 million for each re-use, down 25.9%. Two times can be reduced by 36.3%. If the two-stage is also reusable, the cost of a rocket can be reduced to 10% of its initial cost when it is launched 10 times and 1% when it is launched 100 times [9].

4. Launch Mode on board
The carrying and launching mode here is not traditional carrying, but uses reusable carriers to carry the orbiter to a certain height and release the ignition and launching. Like small launch vehicle “Bloostar” of Spanish Zero2infinity, which uses warm balloons as its base stage to launch it into the air, then fires to put payloads into orbit. Similarly, “Launcher-One” and “Pegasus” small launch vehicles of virgin galactic use the aircraft as a base class, and after launch, the plane's landing is like its base class recovery.

4.1 Structure Design

“Bloostar” has chosen a unique three-stage parallel configuration. the first and second sub-stages adopt annular tanks. the first sub-stage surrounds the second sub-stage and the third sub-stage is in the center position. as shown in figure 5. This circular configuration makes the rocket compact and easy to assemble. The use of a balloon to rise to the edge of space and reignite the launch is almost impervious to air resistance. Therefore, the design of shape is not restricted by aerodynamics. To avoid the influence of atmospheric environment, the fairing is designed in a collapsible form, with a carbon fiber framework and a multilayer composite surface, the inner layer of which is a gas barrier film.

4.2 Propulsion System
“Bloostar” has six liquid-oxygen/methane engines at one sub-stage, each providing 15kN thrust, and six liquid-oxygen/methane engines at 2kN thrust at the second stage. The engines of the second stage and the third stage are the same, but only one. The first and second stage tanks are made of carbon fiber composite materials wrapped together. The interior is equipped with anti-sloshing plates to prevent the low-frequency shaking of the propellant. The surface tanks is also coated with multi-layer insulation materials to control the evaporation loss of the propellant. In addition, all tanks are pressurized with helium to maintain the overall structural strength of the rocket, as shown in table 4 for the parameters of the methane engine used in the “Bloostar” first stage. The use of an aircraft to carry an orbiter is more restrictive than “Bloostar” uses balloons to bring the orbiter to its intended altitude.

The engine is used in high altitude, low pressure and vacuum environment, so the engine nozzle can be optimized in a single working environment to achieve optimal performance. The engine size is small, and 3D printing technology can be used. In terms of the development of liquid oxygen methane
engine, Shanghai aerospace academy plans to develop a new reusable vehicle using liquid oxygen methane engine after 2020, realizing more than 20 times of reuse, and the launch cost is expected to be reduced by about 30%.

| Table 4. Liquid Oxygen/Methane Engine Parameters [10] |
|---------------------------------------------|
| Vacuum Thrust | 15kN |
| Cell Pressure | 10 psi |
| Vacuum Specific Impulse | 345 |
| Total Mass Flow Rate | 4.4kg/s |
| Propellant | Liquid Nitrogen/Methane |

4.3 Launch Scheme

Figure 6. The left picture shows the relationship between ground launch (red) and 20 km launch (blue) drag and altitude. The right one shows the relationship between heat flux and altitude.

“Bloostar” uses balloons to reach altitudes of 20-25km, followed by three sub-stage engines firing at the same time, providing 104kN of thrust [11]. Figure 6 shows the trajectory and heat flux heat curve of “Bloostar”. Compared with a standard ground launch, the use of a vehicle to transport the orbiter to the stratosphere height can reduce the speed increment needed to enter the orbit. Zero2infinity estimates that, using the ASTOS tools, the balloon is launched at higher altitudes compared to the ground, the speed delta required by the balloon is reduced by 8%, the emission resistance is reduced by about 20 times, and the heat flux is reduced by a factor of 10. In addition, after separation, balloon and other vehicles can be used as high altitude repeater, which saves costs. Using balloon to launch has the advantage of aerial launch, but it has the disadvantage of too long uplift time. Besides, during the flight test, the balloon gas overflow caused by unpredictable gust of wind also occurred, resulting in the balloon damage phenomenon.

4.4 Launch Costs

Zero2infinity plans to launch it in the second half of 2018, a 600-kilometer SSO orbit with a capacity of 75kg, which costs $4.5 million, about $60,000 per kilogram.

5. Airborne Aircraft Mode

The RLV of the space plane model adopts a horizontal landing mode, uses atmospheric resistance to slow down before landing, has excellent rapid response capability and hypersonic flight capability, can develop into a military hypersonic vehicle with strategic deterrence, adapts to the requirements put forward by the new military space application requirements on the space delivery system, and various space powers and mainstream organizations have begun to study their related technologies one after another. DARPA and the Boeing company cooperation project, NASA’s XS-1 X-37 b and India RLV-TD are reusable launch vehicles of Airborne Aircraft Mode.

5.1 Structure Design

The recovery part adopts horizontal landing method, but there are great differences in configuration and launching method. The XS-1 is a vertical launch and a two-stage parallel configuration, the first is
a skyplane configuration, and the first is hunched over the top; The x-37b and RLV-TD are launched vertically, but they need to be put into orbit by an atlas rocket. As shown in figures 7, XS-1 is partially reusable patterns. In the field of pneumatic layout, the three are similar, it's not a purely lift design, it's designed to be called a hybrid body, a blunt head cone shaped body and a slender wing, and a pair of pointy delta wings. In order to install the upper stage on the back of the fuselage, the XS-1 eliminated the double vertical tail, increased the aspect ratio of the wing, and added the trailing edge with the small wingtip of the control rudder face. The belly of the fuselage is designed to be similar to the shape of a flat plate, forming a semi-lift structure similar to the wing, which increases the lift force in the re-entry stage while reducing the wing area, and enhances the maneuverability and endurance performance.

5.2 Propulsion System
The XS-1 is fitted with two SpaceX Merlin1D engines, which were introduced in the introduction of the falcon 9. The AJ26 (NK33) engine is not reusable at the upper stage. The X-37B is equipped with an AR2-3 rocket engine and uses methylhydrazine and N2O4 as propellants. Although methylhydrazine is highly toxic, the technology is relatively mature.

5.3 Thermal Protection System
Both the XS-1 and the X-37B are made of a composite fuselage, using a TUFROC at the leading edge of the hottest wing and the nose wing area. TUFROC is a new type of thermal protection materials, it has been applied to the high temperature area of aircraft, can withstand the high temperature of 1697 ℃, and under the condition of high temperature to maintain strong aerodynamic shape. TUF/AAETB was used in the body's windward and other parts of the body in the sub-high temperature area. In low temperature area leeward side body etc., choose the reusable of CRI Blankets, which can guarantee the durability of the aircraft's aerodynamic shape and thermal protection due to its structural properties [12]. However, there are also disadvantages to heat shield. First, all the equipment is arranged on the surface of the body. Second, it increases the body weight and reduces the payload mass. In addition to the heat shield, the XS-1 has added an insulating layetabler on the outside of the fuselage, using a hard, smooth coating on the outside.

5.4 Recycling Scheme
The return phase of XS-1 is the same as the “bobcat III” horizontal landing mode proposed by XCOR, as shown in figure 8. It uses a horizontal landing approach originating from the space shuttle. Although the horizontal landing recovery method can recycle the expensive space equipment, it still faces the test of autonomous landing technology, re-entry atmospheric return technology and thermal protection system. And it has to lower the cost of recovery maintenance, or it is going to go the way of the shuttle. Just like the X-38 recovery is also horizontal landing, but it has no power to taxi in the
re-entry process, and then uses the wing umbrella to slow down the landing. Compared with the horizontal landing of the wing, the use of the wing umbrella can reduce the consumption of propellant, but also lead to the reduction of the payload carrying capacity.

5.5 Launch Costs
In 2014, DARPA applied for $10 million in research grants for the first phase of the XS-1 project, with a $140 million budget for the second phase. The XS-1 is designed to be a reusable military space jet, with a payload of 1360kg, 10 consecutive satellite launch missions in 10 days, and each launch costs $5 million [13].

6. Summary
Based on the above analysis and taking reliability and low cost into consideration, the following Suggestions are put forward for the research of reusable launch vehicle:

1) Throughout the development history of RLV, the mainstream technological approach for development is to develop new technologies and construct new configurations and design a vehicle that is very different from the traditional one-time carrier rocket. The pursuit of advanced technology will also bring great risks. Like America's space shuttle, excessive pursuit of technology advancement, finally do more harm than good. The focus of development should be shifted from the pursuit of advanced technology to the goal of high reliability and low cost.

2) At the present stage, RLV should take rocket power as the main body and inhale combined power as the future development direction. In the 1990s, after the failure of many countries' aspirated single-stage in-orbit aircraft program due to the great technical difficulties, they all chose the gradual development model successively. So at this stage, we need to develop a more mature rocket power, and on the basis of the original launch of the rocket-propelled rocket, the development of a propulsion system that is more suitable for RLV.

3) Thermal protection system has always been a technical difficulty that restricts the development of RLV and is also the core part of RLV. In order to solve the heat matching problem in high temperature area, X-37B put forward the idea of thermal insulation integrated design. In this regard, the core is to improve the practicability and economy of reusable thermal protection materials for carriers, upgrade the performance of thermal protection structures and materials in different temperature zones, and enhance the reusability and structural lightness of the thermal protection system.

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