Development and the State-of-Art Facility for Aerospace Vehicle

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Abstract. Aerospace vehicles is the platform of next generation transportation as well as a compulsory tool to investigate expletory. However, the space technology hasn't really had a breakthrough progress. On this basis, this paper will discuss the current development history, progress as well as demonstrate the state-of-art facilities for aerospace vehicle. To be specific, the structure, propulsion and material of the aerospace vehicles in different era will be introduced with detail parameters. According to the analysis, although the core propulsion form remains unchanged as chemical propulsion, progress in safety has been almost accomplished. In addition, the thermal protection material took the advantage from old but mature technologies. To better illustrate the statements, schematically visualizations have been demonstrated. At the same time, the drawbacks and defects of current facility as well as future prospects for the improvements of the designs are proposed accordingly. Overall, these results shed light on guiding further exploration of aerospace vehicle.

Keywords: Space Shuttle; Space Launch System; Orion Spacecraft; Falcon 9 Rocket.

1. Introduction

Transportation has always been an extremely important factor for the operation of the world. In the Age of Exploration between15th and 17th century, extent of globalization vastly increased, creating new trading routes that exchange goods, people and knowledge. Similar to the sailing technology enhancement during that time, nowadays we have extended our transportation means to space. In October 4th, 1957, the Soviet Union successfully launch the first satellite, and in April 12th, 1961, Yuri Alekseyevich Gagarin successfully reached out to space, symbolizing the humankind can break the block of gravity [1-5].

As time pass, the aerospace vehicle also evolved from Vostok 1 to Apollo, to Space Shuttle, and to Orion. The space sailing distance increased from orbiting earth, to moon, and even toward Mars. As the materials and avionics has improved greatly since the first spaceship launch, the propulsion system has not increased significantly. From Vostok 1 to Space Transportation System, to Space Launch System, to Falcon 9, all of them use chemical rocket engines that take liquid oxygen and liquid hydrogen or kerosene as fuel. There is, indeed, other forms of propulsion, such as electric propulsion and solar sail. However, nearly all those newly development propulsion techniques had little propulsion, making them not applicable at all during the first stage of launching, which is escaping the gravity of earth. They do, have other advantages. For example, the propulsion of electric propulsion engines can be very precisely controlled, making it very suitable for satellites in adjusting its direction while in orbit. Solar Sails are used on deep-space detectors since the propulsion from the sunlight is free but tiny.

Although the main rocket engines didn't really have a revolutionary change, there is indeed improvements. In this paper, the development as well as the state-of-art facilities for aerospace vehicles will be demonstrated. To be specific, the rest part of the paper is organized as follows. The overall description and structure of aerospace vehicles in different era will be introduced in the Sec. 2 and Sec. 3, respectively. Then, there will be a more detailed analysis on the engines and the materials in Sec. 4 and Sec. 5, respectively. Subsequently, the current limitations as well as the future prospects will be proposed in Sec. 6. Eventually, a brief summary will be presented in Sec. 7.

2. Description

There are 2 main styles of aerospace vehicle in human history. One was the form of the space shuttle, which has stopped since the end of the last space shuttle mission in July 21, 2011 [1]. The other is the mainstream style in current time, the manned rockets, such as the combination of Orion Spacecraft and the Space Launch System as shown in Fig. 1, or the combination of Dragon Capsule and rocket Falcon 9 rocket. The space shuttle usually consists of 4 parts: 2 solid rocket boosters, an external tank, and orbiter, which is the core of the combination and the real "space shuttle" where the astronauts stay.

The propulsion to overcome the gravity is provided by the 3 main RS-25 engines on the orbiter and the 2 solid rocket boosters. The external tank stores liquid oxygen and hydrogen for the RS-25 engines [2, 3]. In these 4 parts, the solid rocket boosters and the orbiter could be reused, while the external tank would be abandoned after each launch mission [5]. The Space Launch System is very similar to the launch system of space shuttle. They both use RS-25 engines and solid Rocket Boosters to break through the atmosphere. What's different is that the orbiter that act as a glider while returning to earth is replaced by Orion Spacecraft which uses parachute for return [2]. There are other small differences that I would include in later parts. If the space shuttle represents the past while the SLS system represents the current, Falcon 9 from SpaceX represents the future of space transportation. By realizing retrievable rockets that could be reused quickly, the SpaceX greatly reduce the cost of space launching, making space travel not limited to government. The first stage of Falcon-9, which is able to fly back to land by itself and could be refilled quickly for the next launch mission, use nine Merlin engines that use liquid oxygen and rocket-grade kerosene (RP-1) as fuel, which is safer and cheaper [6]. Although other parts of the Falcon 9 is not reusable, the price of launching is massively reduced since the first stage of the Falcon 9 is the most expensive part of the rocket [6]. The launch price of the Falcon 9 is $67 million, while the SLS cost about $2 billion per launch [7-9].

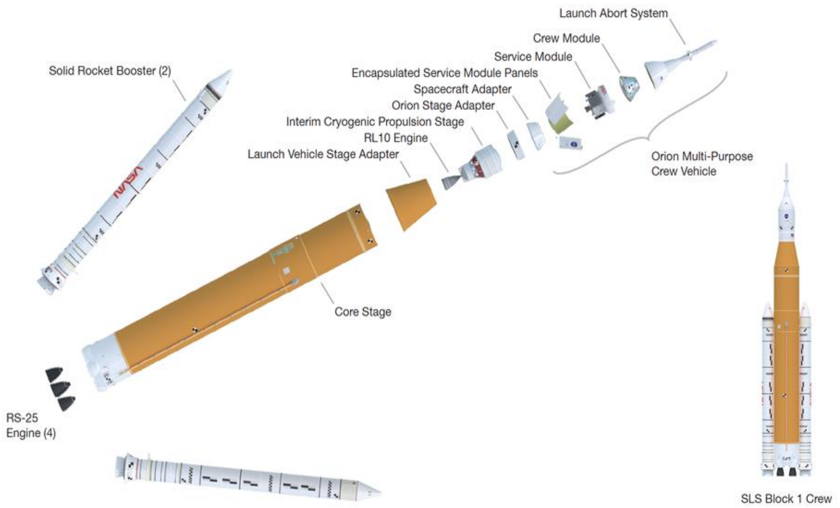

Fig. 1 Space Launch System and Orion Spacecraft.

3. Structure

The structure design of the orbiter is very similar to an airplane. In fact, the way of the reentry of the orbiter is similar to a glider [10]. Since the engine doesn't fire during the reentry, all the acceleration is provided by earth's gravity. In other words, the orbiter may need to have enough lift with a velocity that is decreasing. Thus, the orbiter has double delta wing configuration. This design could reduce the friction during hypersonic speed while providing a good lift-to-drag ratio during landing [11]. The lift of the wings is created by the difference of pressure caused different speed of air flow in the upper and bottom side of the wings. The faster air flows, the less the pressure it has. Thus, most wings of airplane have an upper surface that is curved out and a flat bottom surface to create different speed of air flow, causing a pressure difference above and below the wing and generating the lift. Usually, if the curvature of the upper surface is bigger, there will be a great difference in speed of air flow, and thus a greater lift. But the more curved upper surface would also create bigger resistance. Thus, a big lift-to-drag ratio needs special design of the wings, such as delta wings. With a good lift-to-drag ratio, the orbiter could maintain enough lift by losing its velocity slower. As illustrated in Fig. 2, the main body of the orbiter can be divided into 3 parts: forward fuselage, mid fuselage and aft fuselage. The forward fuselage is mainly occupied by the crew module and its support facilities. The crew module is 65.8 cubic meter and contains 3 sections: flight deck, mid deck and airlock [12]. The flight deck is very similar to the cockpit of an airplane, with hand controllers and rudder petals.

However, it is far more complex than cockpits, with more than 2020 separate displays and controls. The mid deck is mainly the living quarters of the astronauts. It contains sleep stations, waste management system, personal hygiene station, dinner table, and provisions such as provisions and stowage facilities. The airlock provides access for spacewalks and contains 2 spacesuits and mobility aids. The mid fuselage mainly contains the cargo bay and the Remote Manipulator System, a 15.2m long articulating arm remotely controlled in the flight deck. The aft fuselage contains the RS-25 engines, orbital maneuvering system, body flap, vertical tail, and external tank rear attachments [12].

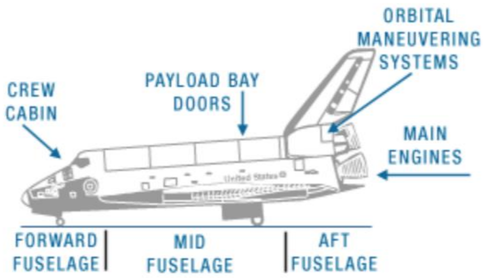

Fig. 2 Structure of Space Shuttle.

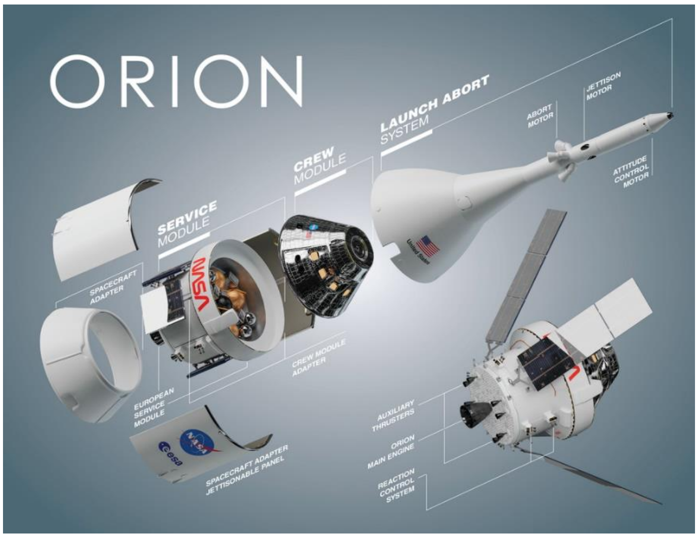

Fig. 3 Structure of Orion Spacecraft.

As exhibited in Fig. 3, the Orion Spacecraft can be divided into 3 parts: the launch abort system, the crew module and the service module. The launch abort system, powered by small solid rockets, will carry the crew to safety if an emergency happens [12]. The crew module is designed to be able to sustain 4 astronauts for up to 21 days without docking to another spacecraft. The fundamental structure of the crew module is a pressure vessel made up by seven large aluminum alloy pieces that are joined using friction-stir welding, creating a strong, light weight, airtight capsule. The crew seats will be attached the flow structure inside Orion, which is also the stowage locker that stores the equipments. This structure is an aluminum structure of crisscrossing beams [13].

The crew module also has a reaction control system consist of 12 small engines. This system helps the capsule to be oriented with heat shield facing downward during reentry. The service module is the powerhouse of the spacecraft, providing electricity, propulsion, thermal control, air, and water to the crew module. There are 33 engines in total on the service module, with 1 main engine, eight auxiliary engines and 24 reaction control thrusters. The main engine and auxiliary engines provide orbit maneuver abilities, and the reaction control thrusters help the steering and control of Orion while in orbit. The service module uses 4 solar array wings to generate electricity that can powering 2 three-bedroom homes. The service module also contains tanks storing water, oxygen and nitrogen [13].

4. Propulsion and Fuel

Engines are one of the most important parts of an aerospace vehicle because if offers the propulsion of the vehicle that is necessary for various space missions. Thus, the performance of the engine is very important. One way of measuring the power of the engine is its thrust-weight ratio. The calculation of this ratio is relatively simple, where you just divide the thrust produced by the engine by the weight of the engine. On a basic level, engines with bigger thrust-weight ratio are better. Only engines with big enough thrust-weight ratio can sent devices, cargos or humans up into space. This is because acceleration of the aerospace vehicles must be extremely big to grant the vehicle enough speed to stay on the orbit or get rid of the influence of earth's gravitational force. Nowadays, those engines are usually chemical rocket engines, using solid or liquid fuels. These engines spill hot gases downward to create upthrust because of the Newton's third law and the conservation of momentum.

The main rocket engines that are used by the NASA is the RS-25 engine. The RS-25 engines was first developed in 1972 by Rocket-dyne as the Space Shuttle Main Engine [9]. The thrust-weight ratio of it is 512300 lbs/7800 lbs = 65.68. It is a "pump-fed staged-combustion rocket engine" that burns liquid oxygen and liquid hydrogen. As depicted in Fig. 4, it is mainly composed of 2 low-pressure turbopumps, 2 high-pressure turbopumps, 2 preburners, main combustion chamber and nozzle. The engine is "staged" because the oxygen and the hydrogen would mix and burn in the preburners first. the mixed gas is ready for combustion in the main combustion room. It is "pump-fed" as the hot gas in the preburners would propel the spinning of the turbines, and pushing more oxidizer and fuel into the preburners. AS the RS-25 engine was first developed for the orbiter of the space shuttle program, it was designed to be reusable with a service life of 55 starts and 27000 seconds [9].

However, after the retirement of the Space Shuttles, RS-25 engines was selected as the core stage engine of the Space Launch System because of the large amount of experience gained from 135 missions, almost 3000 ground tests, and over 1 million seconds of total accumulated hot-fire time. However, there was many adjustments need to made in order to integrate the RS-25 engine into the SLS. For example, while the exit plane of the RS-25 engine nozzles on the shuttle was about 4 meters above the exit plane for the solid rocket boosters, those exit planes are barely on the same level in the SLS, causing an increase in thermal load on the RS-25 engine nozzles. Thus, the injection-molded ablative insulation is applied on the RS-25 nozzle to prevent the nozzles from damaging [9].

Other than the RS-25 engine, the Merlin engine developed by the SpaceX is relatively a more powerful engine because it has a bigger thrust-weight ratio and a better structure. This engine use kerosene and liquid oxygen as propellent, which is safer and has a bigger energy intensity than liquid hydrogen [11]. Although the thrust of the Merlin engine is only 190000 lbs at sea level, it has a weight of only 1030 lbs, making the thrust weight ratio 184, almost 3 times of the RS-25 engine [11, 12]. Moreover, the Merlin engine utilizes high pressure kerosene as the hydraulic fluid, eliminating the need for a separate independent hydraulic system [14]. This design greatly reduces the complexity of the engine and remove the possible accidents caused by the leaking of hydraulic fluids. In fact, portion of launch failures caused by the hydraulic system is relatively large. As presented in Fig. 5, while the propulsion system problem causes 54% of the total failures, feeding system and pipes & valves contribute 65% failures in the propulsion system section [15]. These two component parts of the liquid rocket engine are usually controlled by hydraulic systems. Thus, by reducing the complexity in the hydraulic system, the possibility of error occurring in this system could be reduced, and increase the reliability of the Merlin engine greatly.

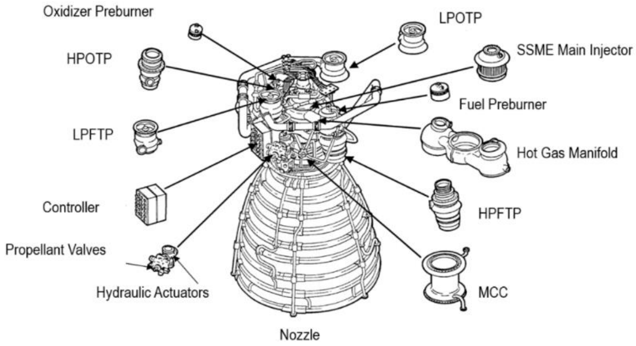

Fig. 4 Components of the RS-25 rocket engine.

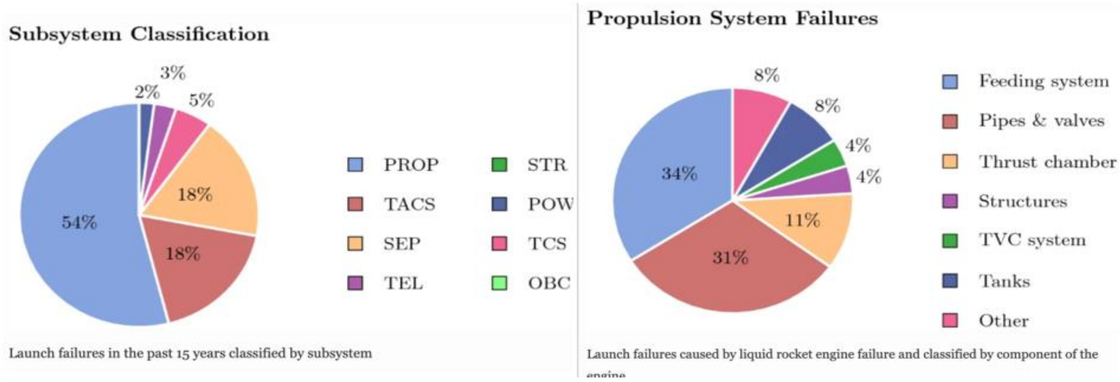

Fig. 5 Distribution of the causes of Launch Failures.

5. Material and thermal protection

One of the biggest problem when a aerospace vehicle returns to ground is the extremely high temperature. While part of the heat comes from the friction between the vehicle and atmosphere, most of the heat is caused by rapid air compression without time for the air to cool off. This temperature varied with the re-entry speed of the vehicle, but even the space shuttle, which have a relatively smaller re-entry speed of 7.5 km per second, still generates a temperature of 1593 degree Celsius, a temperature that is able to melt iron and nickel [16]. Thus, the Thermal Protection System was developed to prevent the structure of the aerospace vehicles from deformation and even melting. It is also responsible for protecting the vehicle from extreme low temperatures in space. There are 2 types of TPS, ablative and reusable [17]. Since the space shuttle was designed to be reusable, it uses reusable TPS. Because of the different critical temperatures at the different positions of the shuttle and the weight impact of the TPS, the TPS design on the orbiter used multiple TPS materials [18]. Because the tip of the orbiter and the front edge of the wings need to endure the highest temperature, they are covered with Reinforce Carbon-Carbon Panels.

This material could withstand temperatures up to 3200 degree Fahrenheit. The High-temperature Reusable Surface Insulation(HRSI) is mainly composited by Alumina Enhanced Thermal Barrier, a material with good thermal stability. The FRSI blankets that covered the upper surface of the wings and the cargo doors are composed of Nomex felt coated with silicone rubber paints It could insulate temperature from 350 F to 700 F, suitable for shuttle's top which usually reaches temperature around 600 F [18]. The AFRSI have a core of silicon felt between a layer of silica fabric and a layer of glass fabric, covering the side of the shuttle and the tail fin [18]. In contrast to the reusable TPS on the space shuttle, the TPS on Orion Spacecraft, one of the mainstream manned aerospace vehicles, is ablative. This is because the whole capsule is not designed to be reusable. The main component of the Orion TPS is the heat shield that is located at the bottom of the command module. During the first flight, the Orion used avcoat, which is the same material used in the Apollo missions. This material is an epoxy novolac resin with special additives in a fiberglass honeycomb matrix that could control the surface of the capsule within 600 F during reentry [18]. However, the structure of the matrices is advanced to titanium for the Orion to reduce weight and increase strength [19]. The back shell of the Orion capsule is covered with AETB-8, the same material used for the HRSI in the orbiter [19].

6. Limitations & Prospects

The current aerospace vehicles have various limitation. The most important limitation is the extremely high cost of launch. This is mainly caused by the current mainstream design of the aerospace vehicles, the capsule style, is not reusable at all. Even the solid rockets in the SLS, inherited from the reusable solid rocketed boosters in the space shuttle program, is no longer reusable because of the elimination or parachutes. In the capsule style aerospace vehicle, usually all the components are not reusable. The high cost induced by this causes that space travel could hardly be commercialized. There are a few people who can afford space travel. As the demand of space travel decreases, hence is the improvement in technology. The space propulsion technique hasn't really had a breakthrough development. Chemical boosters are still the main propulsion source for more than 60 years. Thus, decreasing the cost of space travel to the degree of airplanes is necessary for the development of space travel technologies.

7. Conclusion

In conclusion, this paper investigates aerospace vehicles based on NASA and research papers. Specifically, this paper studies the structure, propulsion and fuel, and material and Thermal Protection System on the aerospace vehicles in different eras. According to the analysis, although the way of rocket engines to produce propulsion haven't advanced, new engine structures have developed to increase reliability and safety. Moreover, a lot of spacecrafts in current time tend to use technologies that were developed in the 20th century, such as the TPS material on the Orion Spacecraft is almost the same as the one on the Apollo Spacecraft. In addition, the structure of the modern spacecrafts is basically the same with first spacecraft Vostok 1, mainly consist of a crew module and a service module. Nevertheless, there is limitation to this paper because nearly all the information comes from NASA, so there is a possibility that there is already new space travel technology developed but have not put in use. In the future, if the cost of space travel decreases to the extent of the price of airplane tickets, space travel will become full commercialized and further motivate the technology improvements in space travel. Overall, these results offer a guideline for the overall structure and technology development on aerospace vehicles.

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