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Force analysis of rocket in flight

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Abstract. At 9:00 Beijing time on October 15, 2003, the Long March II F rocket was successfully launched into space, and the ShenZhou V manned spacecraft carried by it was also China's first manned rocket launched into space. Yang Liwei, the ShenZhou V astronaut, became China's first astronaut , which also showed the great progress of China's space industry. This paper studies the Long March II Series rocket piloted by Yang Liwei, and analyzes the forces on the rockets in the expected state from the aspects of aerodynamics, basic mechanics, and gravity through the Long March II rocket parameters published to the public. The final data shows that air resistance and gravity will cause a great consumption of the rocket fuel.

Keywords: Long March II, Yang Liwei, force analysis, aerospace, aerodynamics.

1. Introduction

At 9:27 a.m. on June 17, 2021, the Long March II F (CZ-2F) carrier rocket successfully launched the ShenZhou 12 manned spacecraft, carrying Nie Haisheng, Liu Boming, and Tang Hongbo into the scheduled orbit [1]. This is the latest record of China's launch of the Long March II manned rocket. This rocket has made some improvements in terms of the use of external materials or the technology of internal electronic components compared with the Long March II polited by Yang Liwei 18 years ago. Therefore, the author hopes to help China further optimize the Long March II rocket in the future by studying the force on the Long March II rocket in several classic flight stages, including the take-off, the mechanical values of booster separation, the primary engine separation, and other stages. The force values are obtained by using rocket parameters and mathematical formulas, and the force on the rocket is introduced. As China's main payload rocket, the Long March II series rocket may be able to help with the rocket optimization in the future if it can be analyzed from the force of each stage of the rocket launch.

2. Background information

On May 17, 1958, Chairman Mao Zedong issued a call at the second session of the Eighth National Congress of the Communist Party of China: "we should also build artificial satellites" [2]. China's aerospace industry has officially begun since then. From the 1960s to the 1990s, China's aerospace engineering has made rapid progress. In the 1970s, China successfully developed the "Long March 1", "Long March 2", "Long March 3", and "Long March 4" series carrier rockets. In the late 1980s, based on the above models, the launch vehicles such as "Long March 2E", "Long March 2F", "Long March 3A", "Long March 3B", "Long March 4A", and "Long March 4B" were successively developed [3].

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The rocket discussed in this paper, the Long March II series carrier rocket, is a low earth orbit carrier developed by China, and its development began in 1970. Before the 21st century, the Long March II series was composed of four models: Long March II (first launched in 1974), Long March II C (first launched in 1982), Long March II E (first launched in 1990), and Long March II D (first launched in 1992). Among them, the production of Long March II was stopped in 1979.

The Long March II rocket, which has been discontinued, is the first rocket of the Long March II series. It was launched for the first time at the Jiuquan launch center on November 5, 1974. However, due to a hidden injury and fracture of a wire in the control system on the rocket, the attitude lost control and the flight test failed. On November 26th, 1975, the second Long March II was successfully launched, putting China's first recoverable satellite into the predetermined orbit accurately. On this basis, the design of Long March II is further improved, and the improved Long March II, Long March II C, is the main analysis object of this paper.

3. The structure, parameters, and launch process of Long March II C Rocket

3.1. The structure of Long March II C rocket

The Long March II C can be roughly divided into five parts: fairing, instrument cabin, secondary arrow body, primary arrow body, and tail (Figure 1). The instrument cabin is located in the forefront of the Long March II rocket and is mainly equipped with some essential segment control facilities. There are two stages of the rocket body. The first-stage rocket body is the main thrust source of the rocket. The rocket will separate the first-stage rocket body at a certain height to reduce the weight of the rocket, so as to reduce the thrust of the second-stage rocket body and make the rocket fly longer.

3.2. The structural parameters of Long March II C rocket

Table 1 mainly shows the detailed parameters of the Long March II and the detailed numerical introduction of the disassembly of the main parts of the rocket.

3.3. The launch stages of Long March II C rocket

Figure 2 roughly decomposes the general rocket launching process and divides the process into several different stages. The launch I process of Long March II is shown below [4]:

1. Take off.
2. Booster engine shutdown.
3. Booster separation.
4. The engine of the first sub stage is shut down.
5. Separation of primary and secondary sections.
6. Payload fairing separation.
7. The main engine of the second sub stage section is shut down.
8. The traveling engine of the second sub stage section is shut down (payload/launch vehicle enters low earth orbit).
9. Payload orientation start.
10. End of payload orientation.
11. Starting rocket ignition.
12. The work of the starting rocket is over.
13. Payload separation.
14. Launch vehicle lateral collision avoidance rocket ignition.

4. Force analysis of main stages in the rocket launch process

The analysis mainly focuses on the force analysis of the rocket around the four forces of air resistance, lift, gravity and thrust. The main formulas are as follows:

$$\text{Air resistance formula:} \quad F_w = C \times \frac{1}{2}\rho v^2 \times S \tag{1}$$

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$$\text{Gravitational formula: } F_g = G\frac{m_1 m_2}{r^2} \tag{2}$$

$$\text{Lift formula: } L = \frac{1}{2}\rho_\infty V_\infty^2 \times S \times C_L \tag{3}$$

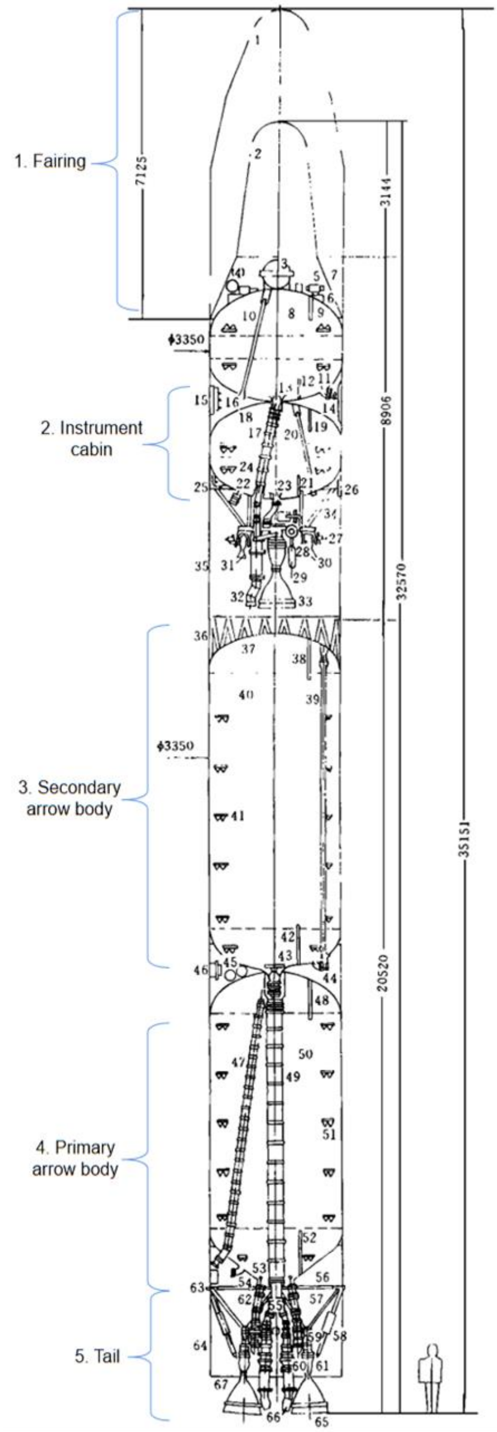

Figure 1. Layout of Long March II C [5].

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Table 1. Main parameters of Long March II C [5].

# of rocket stages	2
Full length of rocket	31.170m(Type-A fairing)
	35.151m(Type-B fairing)
Maximum diameter	3.350 m
Takeoff quality	≈192 t
Thrust weight ratio	1.48
Carrying capacity	2400 kg
Launch speed (at the end of the third second)	38 m/s
Takeoff thrust	2786 kN
First sub segment	**parameter**
Length	23.720 m
Diameter	3.350 m
Takeoff quality	151 t
Structural quality	8.6 t
Propellant mass	143 t
First sub segment thrust	2786 kN
Ground specific impulse	2540 (N×m)/kg
Second sub segment	**parameter**
Length	8.706 m
Diameter	3.350 m
Takeoff quality	38.2 t
Structural quality	3.2 t
Propellant mass	35 t
Vacuum thrust	720 kN
Vacuum specific impulse	2834 (N×s)/kg
Fairing	**parameter**
Length	3.144 m（Type A）
	7.125 m（Type B）
Diameter	2.200 m（Type A）
	3.350 m（Type B）
Effective volume	3.6m3（Type A）
	27m3（Type B）

4.1. Takeoff phase

In an ideal state, a rocket is located on the earth when it takes off, so it is affected by the gravity of the earth. The calculation is the gravity at the moment when the rocket is launched, and the launch site of Long March II C is the Jiuquan satellite launch base, which is about 1000 meters above the sea level and will not have too much impact on the gravity calculation. Therefore, the average radius of the earth can be directly used here, that is, 6.37 × 106 m. The known mass of the earth and the Long March II C and the gravitational constant can be used to calculate the gravitational force acting on the rocket.

In the standard case, the air density around the rocket is 1.29kg/m3, because the altitude is not high during the take-off phase. The front end of Long March II C presents a tip shape, and the drag coefficient C is 0.2. From Table 2, it can be found that the maximum diameter of the rocket is 3.350m, and the height of the fairing (type b) is 7.125m. So the first step is to calculate the side length of the fairing with trigonometric function (here the fairing is regarded as a cone). The second step is to calculate the side surface area of the fairing, which is the contact area s of Long March II rocket C. Finally, with the help of the known velocity V, The air resistance of the Long March II C rocket during the take-off phase can be calculated (shown in Table 2).

Since the rocket has not yet been lifted to a high altitude or tilted too much at this stage, the lift received by the rocket here is temporarily ignored. The thrust of the Long March II C rocket in the take-off phase is brought by the first sub-stage engine, so the rocket thrust here can be obtained in Figure 1.

Table 2. The calculated value of the Long March II C rocket during the take-off phase.

Air resistance：	7174.42 N	Gravitation：	1.8873×106 N
Thrust force：	2786 kN	Lift：	negligible

4.2. Primary engine separation phase

4.2.1. First and second stage separation of Long March II C. Long March II C adopts the method of thermal separation. When the interstage separation procedure starts, the secondary engine will start first, and then the primary engine will be shut down. When the engine thrust of the second sub stage reaches the predetermined thrust and the engine thrust of the first sub stage decreases to the predetermined thrust, the explosive bolts connecting the first sub stage and the second sub stage will detonate at the same time. Then the first and second sub stages begin to separate under the action of the jet and the thrust of the second sub stage engine, and the jet flame of the second sub stage engine will be discharged from the interstage linkage and the separation surface. The nozzle of the two-stage engine is finally separated from the interstage shell section to realize separation [7].

4.2.2. Force analysis. At an altitude of about 80 kilometers, the first stage rocket engine will be shut down and separated. At this time, the gravity of the earth acting on the rocket will become much smaller, because we not only lose a lot of mass (separate the first sub-stage segment), but also increase the direct distance from the earth's surface to a degree that cannot be ignored. Moreover, the mass and distance are proportional and inversely proportional to gravity. Therefore, the author predicts that the gravity at this stage will be much smaller than that at the takeoff stage. Because the rocket has separated a sub-stage. Then the thrust will be provided by the second stage engine. The thrust can be obtained from Table 2.

Since the Long March II C has reached an altitude of 80 kilometers, it must change its flying posture to face the coming 100 kilometers Carmen line. At this time, the contact area between the Long March II and the airflow is no longer just the tip. The maximum cross-sectional area of Long March II C (which has separated a sub-stage) will be used as the contact area, and because the rocket in contact with the airflow is like a bullet at this time, the drag coefficient C used here is 1.7 [8], and the lift coefficient (lateral force coefficient) Cl at this time is 0. 0000125 [9]. The main purpose of

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Long March II C is to transport satellites, so the rocket will need to keep in a low earth orbit to make a circular motion around the earth, and the Long March II C needs to keep at the first cosmic speed (7.9 km / s). However, as the rocket reached the mesosphere and the thermosphere, the air there is very thin about 1/50000 the density of air at the ground level. Using these data, the air resistance and lift can be calculated (shown in Table 3).

Table 3. The calculated value of the Long March II C reaching the mesosphere and thermosphere.

Air resistance：	5.2411×104 N	Gravitation：	3.9309×105 N
Thrust force：	720 kN	Lift：	3.854×10-1 N

5. Conclusion

To conclude, it can be seen from the data that the Long March II rocket does not use the airflow to generate lift to reduce fuel consumption as the aircraft does. This technique of using the characteristics of nature to reduce fuel consumption is also available in aerospace facilities, namely the satellite, which does not carry much fuel. Satellites mainly depend on the gravity of the earth on them and the centrifugal force generated by the speed when they enter the orbit to keep themselves in orbit and make a circular motion around the earth. Although the Long March II C rocket also uses gravity to reduce the fuel consumption when the it finally returns, it is still too little compared to the fuel it consumes to fight gravity during the launch state. From the data of these two stages analyzed in this paper, it can also be understood that the impact of air resistance and gravity is very large for the fuel consumption of the Long March II C rocket. Therefore, in the future, China's aerospace industry can try to avoid rockets from being contacted with these two forces, air resistance and gravity, as much as possible. Finally, the force analysis in this paper is in an ideal state, so the special situation is not fully considered.

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