

The Significance of Classical Mechanics in the Evolution of Space Exploration

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Abstract: Classical mechanics, developed by Isaac Newton in the 17th century, revolutionized our understanding of motion and gravity. During the Scientific Revolution, Newton's laws of motion and universal gravitation provided a framework to explain celestial and terrestrial phenomena. This knowledge became the foundation for modern physics and engineering. In the 20th century, as the space race began, classical mechanics played a critical role in space exploration. It enabled scientists to calculate rocket trajectories, predict planetary orbits, and design spacecraft. For instance, NASA's Apollo missions to the Moon relied heavily on these principles to ensure safe travel and landing. Even today, as humans explore Mars and beyond, classical mechanics remains essential for mission planning and problem-solving. Without it, achievements like satellite launches, space probes, and human spaceflight would not have been possible. This article will analyze the three laws of mechanics and the law of universal gravitation in classical mechanics, and discuss their impact on human exploration of the universe. Based on the analysis, two main conclusions were found: First, classical mechanics can help humans predict the orbits of planets and satellites, enabling them to better calculate the trajectory and thrust of spacecraft. Second, classical mechanics can enable humans to better plan the structure of spacecraft to enhance its strength and the efficiency of various instruments.

Keywords: Classical Mechanics, Space exploration.

1. Introduction

Space exploration is one of humanity's greatest achievements. It helps people answer big questions, like how the universe began, whether life exists beyond Earth, and what our future might look like. Through space exploration, humans also develop new technologies that improve life on Earth, such as GPS, weather forecasting, and medical advancements.

The journey of space exploration began in 1957 when the Soviet Union launched Sputnik-1, which is the first artificial satellite. This started the space race between the Soviet Union and the United States. In 1961, Yuri Gagarin became the first human to orbit Earth, and in 1969, NASA's Apollo 11 mission successfully landed humans on the Moon. These milestones showed the world what humans could achieve.

A key foundation of space exploration is classical mechanics, developed by scientists like Isaac Newton. His laws of motion and universal gravitation explain how objects move in space and how forces like gravity affect them. Without classical mechanics, people wouldn't be able to calculate

rocket trajectories, plan satellite orbits, or land spacecraft on other planets. It remains essential for understanding the motion of celestial bodies and designing missions.

In recent decades, space exploration has become more collaborative. Like the International Space Station (ISS), which launched in 1998. Robotic missions, like the Mars rovers and the Voyager probes, have explored distant planets and even left our solar system. Today, private companies like SpaceX are making space travel more affordable and accessible, while NASA's Artemis Program aims to return humans to the Moon and eventually reach Mars. This article will demonstrate the importance of classical mechanics in space exploration, by analyzing the three laws of mechanics and the law of universal gravitation in classical mechanics, and discussing their impact on human exploration of the universe.

2. The Three Laws of Mechanics and The Law of Universal Gravitation

The Three Laws of Mechanics, developed by Isaac Newton in his book "Mathematical Principles of Natural Philosophy" in 1687, are the foundation of Classical Mechanics. And this paper will introduce the content about it.

The first law states that any object will remain stationary or in uniform linear motion when the net force acting on the object is zero [1]. This law first explicitly proposed the concept of "inertia" and rejected Aristotle's traditional view that "force is the cause of maintaining motion". For example, when a car suddenly brakes while in motion, passengers lean forward because inertia makes their bodies attempt to maintain their original motion state. The law of inertia provides a reference frame for analyzing the action of forces.

The second law reveals the quantitative relationship between force and motion change, and its core formula is $F=ma$ [1]. This law states that the acceleration of an object is proportional to the applied external force, inversely proportional to its mass, and in the same direction as the force. It is not only applicable to particles, but can also be extended to complex systems through integration. For example, the reaction force of fuel injection in rocket propulsion is calculated using this formula to determine the acceleration change and control the orbit. The differential form of the second law, $F=dp/dt$ (force equals rate of change of momentum), further expands its applicability and becomes a core tool in engineering mechanics and aerospace design.

The third law states that the interaction force between two objects is always equal in magnitude, opposite in direction, and acts on the same straight line. For example, when a person walks, their feet exert a backward force on the ground, and the ground exerts a forward reaction force on their feet to push them forward; at the same time as the rocket engine emits gas, the gas generates thrust on the rocket.

The Law of Universal Gravitation is a physical law proposed by Newton in 1687, which tells us that there is a force of mutual attraction between any two objects in the universe, and this force is called gravity. The strength of gravity depends on the mass of two objects and the distance between them. Specifically, the magnitude of gravity is directly proportional to the mass of two objects, with the larger the mass, the greater the gravity; and inversely proportional to the square of the distance between them, the farther the distance, the smaller the gravitational force. This law can be expressed by the formula $F=G(m_1 m_2)/r^2$.

The Universal Gravitation Law explained why apples fall from trees and why planets orbit the sun through this law. He also used this law to derive Kepler's planetary motion laws and helped scientists discover Neptune. In modern times, the law of universal gravitation is widely applied in aerospace engineering, such as calculating satellite orbits, designing lunar missions, and even helping probes fly to farther planets.

3. The Application of Classical Mechanics in Space Exploration

When conducting deep space exploration, speed has always been a major limitation. It takes several months for a Mars rover launched from Earth to land on Mars, let alone reach other planets that are much farther away compared to Mars. By using classical mechanics, people can use the slingshot effect to accelerate or slow the probe down and save a lot of time. For example, the detector Voyager 1, first taking off during 1977, experienced 2 gravitational slingshots to reach the third cosmic velocity. The change in the velocity of the spacecraft is $\Delta V = 2v \cdot \cos(\theta)$. V is the speed of the planet's revolution around the sun. θ is the angle between its trajectory and the direction of the planet's motion when the spacecraft approaches a planet ($0 \leq \theta \leq 90$) [2].

For spacecraft, it is a bridge for human exploration of the universe, and classical mechanics is the cornerstone of this bridge. From Newton's three laws to the law of universal gravitation, classical mechanics provides solid theoretical support for the design, manufacturing, and operation of spacecraft. It not only helps us calculate the structural strength of the spacecraft to ensure its safety in extreme environments, but also greatly improves operational efficiency by optimizing the propulsion system and orbit design. It can be said that without classical mechanics, there would be no glorious achievements in modern aerospace technology.

Spacecraft face enormous mechanical challenges during launch, orbital operation, and return. Classical mechanics ensures that spacecraft can maintain structural integrity under extreme conditions through static and dynamic analysis. During the launch phase, the rocket body needs to withstand enormous thrust and aerodynamic pressure. Newton's second law helps us calculate the force distribution on the rocket body during acceleration, ensuring that the fuel tank and shell do not deform. For example, the first stage engine of the Saturn V rocket has a thrust of up to 3400 tons, and the load is evenly transmitted to the rocket body through a truss structure, avoiding failure caused by local stress concentration [3]. After entering space, the spacecraft still needs to cope with the challenges of the microgravity environment and thermal stress. The thermal elasticity formula in classical mechanics can predict the expansion stress of materials at high temperatures and guide the design and distribution of insulation tiles. The ceramic insulation tiles of the space shuttle are based on this principle and successfully withstand the high temperature of 1350 °C during re-entry into the atmosphere [4].

Classical mechanics not only focuses on the strength of spacecraft, but also significantly improves their operational efficiency through dynamics and the law of conservation of energy.

In the design of propulsion systems, the Tsiolkovsky formula quantifies the relationship between fuel mass and velocity increment, promoting the development of staged rocket technology. For example, SpaceX's Falcon 9 rocket uses three-stage fuel tank separation to increase the payload ratio to 4%, far exceeding the 1% of traditional rockets [5].

Classical mechanics also plays an important role in track design. Hohmann transfer orbit uses Kepler's law and the formula of universal gravitation to calculate the minimum energy transfer path. One of the applications is when Tianwen-1 and Tianwen-2 were launched to Mars, it adopted the Hohmann transfer orbit that saved lots of fuel and only took 202 days to reach the orbit of Mars [6].

Classical mechanics also provides quantitative standards for the research and selection of aerospace materials, helping to achieve a balance between lightweight and high reliability. In lightweight design, specific strength and specific stiffness become key indicators. The specific stiffness of carbon fiber composite materials far exceeds that of the traditional aluminum alloys, and is widely used in spacecraft structures. For example, the mirror bracket of the James Webb telescope is made of carbon fiber material, successfully reducing weight by 40% [7].

In terms of extreme environmental tolerance, classical mechanics is also indispensable. The Griffith theory in fracture mechanics is used to evaluate the critical crack size of ceramic insulation

tiles, ensuring controllable surface crack propagation during spacecraft reentry [8]. In addition, the Newtonian viscous fluid model predicts the creep deformation of nickel-based alloy turbine blades at high temperatures, ensuring the reusability of the engine [9].

4. Conclusion

Classical mechanics, as the cornerstone of modern aerospace technology, plays an irreplaceable role in the structural design, operational efficiency, and materials science of spacecraft. From Newton's three laws to the law of universal gravitation, these fundamental principles provide a solid theoretical foundation for human exploration of the universe.

In terms of structural strength, classical mechanics helps engineers accurately calculate the stress conditions of spacecraft in extreme environments. Newton's second law is used to analyze the dynamic loads during rocket launch, while the thermoelastic formula ensures that the spacecraft can withstand the high-temperature test during re-entry into the atmosphere. The truss structure of the International Space Station is a classic example of mechanical applications, achieving a perfect combination of high strength and lightweight through carefully designed triangular configurations.

In terms of optimizing operational efficiency, the Tsiolkovsky formula has guided the development of staged rocket technology and significantly improved fuel utilization efficiency. The Hohmann transfer and gravitational slingshot effect in orbital mechanics have significantly reduced the energy consumption of deep space exploration, which has contributed to the success of exploration missions such as Tianwen-1 and Tianwen-2.

In the field of materials science, classical mechanics provides important guidance for the research and development of aerospace materials. By using indicators such as strength and stiffness, engineers can select the optimal materials, such as carbon fiber composite materials and aluminum lithium alloys, to achieve a lightweight design while ensuring strength.

Despite the need to combine modern physics theories such as relativity for corrections under extreme conditions, classical mechanics remains the most fundamental and practical tool in aerospace engineering. In the future, with the development of computational mechanics, classical mechanics will continue to drive new breakthroughs in aerospace technology and assist humanity in exploring more distant space. These fundamental principles not only witness the development of space technology, but will also continue to lead the future of space exploration.

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