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Fundamental Aerodynamic and Propulsion Principles of Aerospace Vehicles Based on Fluid Mechanics and Rocket Dynamics

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Abstract. Aerospace engineering is built entirely upon two core modules taught in university courses: classical fluid mechanics and rocket dynamics. Although university courses cover these theories separately, the logical links between low-speed flow, supersonic aerodynamics and space propulsion are rarely summarized systematically in lecture materials. This papersystematizes the complete theoretical framework using the entire teaching content of the aerospace engineering course delivered by Professor Ian Eames. This study employs document review and theoretical comparison to synthesize flow similarity criteria, governing equations, airfoil theories, shock wave relations, gas turbine cycles and rocket motion formulas, and to compare flow features taught in different course chapters. The study derives from course knowledge that Reynolds number controls viscous flow while Mach number dominates compressible flow; boundary layer and shock waves are the main sources of flight drag; rocket thrust is produced by mass ejection, and Hohmann transfer is the optimal fuel-efficient orbit as taught in orbital lessons. This paper integrates scattered course knowledge into one framework and explains the limitations of ideal theoretical models used in class.

Keywords: Aerospace Engineering, Fluid Mechanics, Aerodynamic Force, Rocket Propulsion, Compressible Flow

1. Introduction

All contents discussed in this paper come from the aerospace engineering course, whose knowledge covers civil aircraft, supersonic vehicles and space rockets mentioned by the lecturer [1]. In class, teachers explained that the lift of a wing comes from circulation, that transonic shock waves reduce aircraft efficiency, and that space vehicles rely on momentum thrust rather than aerodynamic force. However, course handouts divide knowledge into independent chapters: incompressible flow, viscous CFD, compressible aerodynamics, aero engines and rocket orbital mechanics. Students learning this subject can hardly build a complete knowledge structure by reading only separate lecture slides [2]. This paper reconstructs the whole subject framework strictly according to the sequence of course teaching. The paper is arranged following the teaching order: first, basic incompressible flow; second, viscous flow and numerical methods introduced in tutorials; third, compressible flow and jet engine cycles; fourth, rocket propulsion and orbital theories; finally hypersonic flow and re-entry knowledge from extension lectures. This research only reorganizes and compares theories learned from courses without adding extra simulation data. This integrated summary can help course learners understand the internal logic of this subject and support further study of advanced aerospace content after finishing this module.

2. Incompressible flow fundamentals

This section introduces the basic low-speed flow theories covered in the early stage of the aerospace course, establishing fundamental assumptions for all subsequent aerodynamic analysis [2].

2.1. Flow similarity

Course teaching states that wind tunnel experiments must satisfy geometric, kinematic and dynamic similarity simultaneously to ensure experimental data corresponds to real flight conditions. Only fully similar flow fields can provide valid aerodynamic reference data for aircraft design.

Class discussion clarifies that the Reynolds number dominates viscous flow simulation and serves as the primary matching parameter for aircraft wind tunnel tests. In contrast, the Froude number reflects gravitational effects and is only applied to marine and hydromechanical models, and it is rarely involved in conventional aerodynamic experiments.

2.2. Governing equations

Mass, momentum and energy conservation equations constitute the fundamental mathematical system of fluid mechanics. These core formulas are introduced in the first tutorial lecture and lay the numerical foundation for all flow field calculation [3].

The Navier-Stokes equation is defined in the course as the core of viscous fluid mechanics. It describes the dynamic force balance of fluid microelements, including inertial force, pressure gradient and viscous resistance, and governs all real fluid motion.

2.3. Airfoil lift theory

Joukowski transformation is explained as a classic mathematical method that converts ideal circular potential flow into practical airfoil flow fields, enabling theoretical analysis of low-speed wing aerodynamics.

The course corrects the common misunderstanding of lift generation. According to the Kutta-Joukowski theorem, airfoil lift is essentially produced by flow circulation surrounding the wing surface, rather than simple geometric pressure difference [1].

3. Viscous flow and CFD methods

This chapter supplements real viscous flow characteristics ignored in ideal flow theory and introduces basic CFD numerical methods involved in course tutorials.

3.1. Boundary layer features

Viscosity originates from the exchange of molecular momentum inside fluids. Internal friction emerges between adjacent fluid layers with disparate flow velocities, which constitutes the physical

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nature of viscous force. Such molecular-scale interactions dissipate kinetic energy into internal thermal energy, rendering viscous flow inherently irreversible.

Ideal flow theories postulate zero viscosity and permit frictionless fluid motion, yet all real fluids possess viscosity. The critical question lies in whether viscous effects are substantial enough to alter the entire flow field. The Reynolds number, defined as the ratio of inertial force to viscous force, provides a practical criterion for this judgment. At high Reynolds numbers, viscous effects are confined to a thin near-wall layer; at low Reynolds numbers, viscosity dominates the whole flow field. This fundamental distinction leads to different analytical approaches for different flight regimes.

Viscous effects are mainly concentrated in the thin boundary layer adjacent to aircraft surfaces. The course divides boundary layer flow into laminar, transitional and turbulent states, each causing different losses in aerodynamic performance.

Turbulent boundary layers significantly increase skin friction drag. Meanwhile, adverse pressure gradients lead to flow separation, generating large pressure drag. The course concludes that total flight drag mainly originates from these two viscous effects.

Beyond flow regime classification, three practical thickness definitions are widely adopted in engineering design. The nominal boundary layer thickness refers to the normal distance from the wall where local flow velocity reaches 99% of the external free-stream velocity. Though conceptually intuitive, this metric is hard to measure precisely in experiments. Displacement thickness quantifies the outward offset of external streamlines induced by retarded flow within the boundary layer. Momentum loss thickness measures the total momentum deficit caused by wall friction. These three thickness parameters serve different purposes: nominal thickness indicates the overall range of viscous influence, displacement thickness is critical for external aerodynamic contour design, and momentum loss thickness directly correlates with skin friction drag calculation. Mastery of these definitions provides an essential foundation for interpreting experimental and CFD data.

3.2. CFD numerical methods

Three classic CFD approaches, including FDM, FVM and FEM, are introduced and contrasted in the course. The finite volume method is widely preferred for aerospace simulation because of its excellent conservation properties and numerical stability [4].

Lectures emphasize that mesh quality and turbulence model selection are the two dominant error sources in numerical simulation. Poor mesh structure or mismatched turbulence models will cause significant discrepancies between simulation results and actual flight aerodynamic data.

4. Compressible flow and air-breathing propulsion

As the central teaching module of the course, this chapter covers high-speed compressible flow characteristics, shock-wave theories, and aero-engine working cycles.

4.1. Mach flow and shock waves

When local airflow velocity reaches sonic speed, transonic shock waves appear on the wing surface. The course illustrates that sudden pressure rise caused by shock waves triggers boundary layer separation, severely reducing aircraft lift and increasingdrag [5].

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Class content compares normal shock and oblique shock structures. Oblique shocks adopted by supersonic inlets produce significantly lower total pressure loss, which is the key reason for the high efficiency of supersonic air-breathing aircraft. Expansion waves also enable continuous flow acceleration in supersonic channels.

Expansion waves and shock waves are two fundamental wave phenomena in supersonic flow with opposite characteristics. Shock waves decelerate airflow while elevating pressure and temperature, whereas expansion waves accelerate flow with simultaneous pressure and temperature reduction. This contrast is critical to the design of supersonic nozzles and inlets. An expansion wave represents the aggregation of countless weak expansion waves generated continuously around convex corners. Unlike shock waves that incur total pressure loss and extra drag, expansion waves enable efficient acceleration of supersonic airflow and act as the physical basis for thrust generation in supersonic nozzles.. This contrast is frequently cited in the subsequent air-breathing propulsion module.

4.2. Engine thermodynamic cycles

Otto and Diesel cycles are briefly introduced as traditional internal combustion cycles, which are applicable only to low-speed propeller aircraft and are not applicable to high-speed aerospace propulsion systems.

All turbojet and turbofan engines follow the Brayton cycle. The course stresses that inlet and nozzle matching directly determinesthe working efficiency of the engine under subsonic, transonic and supersonic conditions, a principle that is central to the design of modern air-breathing propulsion systems [6].

5. Rocket propulsion and orbital mechanics

This independent module explains rocket propulsion theories that are independent of the atmosphere and deep-space orbital maneuver knowledge taught in the latter stage of the course.

5.1. Rocket thrust principles

Rocket engines differ essentially from air-breathing engines introduced in prior chapters. Air-breathing systems take in atmospheric oxygen as oxidizer, restricting their operation to the atmospheric environments; rockets carry oxidizer and propellant on board, enabling independent operation in vacuum outer space. This core difference makes rockets the only viable propulsion solution for space travel.

The course summarizes three core working stages of rocket engines. Propellant (fuel and oxidizer) is pumped into the combustion chamber under high pressure via turbopumps. Intense combustion reactions then occur inside the chamber to produce high-temperature, high-pressure gas. Finally, the hot gas expands and accelerates through the nozzle and is ejected at ultra-high speed, generating reaction thrust in accordance with Newton's third law. Lectures also mention that turbopumps are among the most complicated and failure-prone components of liquid rocket engines, and their technical difficulties constitute a major bottleneck for the development of large liquid launch vehicles.

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5.2. Orbital maneuver theory

Single-stage rockets are limited by structural mass ratio. Multi-stage rocket design effectively reduces structural weight and greatly improves the orbital velocity increment, which is essential for entering high Earth orbit and deep space missions.

The course regards Hohmann transfer as the most fuel-efficient interplanetary trajectory. In addition, the Oberth effect and gravity assist technology are introduced as core propellant-saving techniques for deep-space exploration, significantly improving orbital maneuver efficiency [7].

6. Hypersonic flow and re-entry technology

This chapter summarizes the advanced course content on hypersonic aerodynamic features and atmospheric re-entry protection technology.

6.1. Hypersonic flow characteristics

Under hypersonic conditions where Mach number exceeds 5, extreme aerodynamic heating causes dissociation of air molecules and generation of plasma. The real gas effect departs from ideal gas assumptions and significantly changes high-speed flow field structures.

6.2. Re-entry thermal protection

The course emphasizes the classic blunt body thermal protection theory. Blunt aerodynamic shapes push shock waves away from the vehicle surface, concentrating most thermal energy in the external flow field and greatly reducing surface heat flux [8].

With reference to orbital mission cases in lectures, hypersonic re-entry vehicles adopt composite deceleration methods including supersonic parachute deceleration and reverse jet braking, realizing stable and safe landing in thin planetary atmospheres.

Two mainstream hypersonic aerodynamic configurations are widely discussed: waverider and lifting body. The waverider design leverages shock wave pressure generated on the vehicle's lower surface to produce lift, with shock waves attached to the leading edge to trap high-pressure gas beneath the fuselage. Its primary advantage is a high lift-to-drag ratio, suitable for long-duration hypersonic cruise missions. Lifting bodies generate aerodynamic lift through flattened fuselage surfaces, with design emphasis placed on flattened cross-section geometry. In comparison, lifting bodies feature superior internal volume utilization, making them ideal for missions requiring large payload capacities or propellant storage volumes.

A comparative analysis of the two configurations reveals that waveriders deliver superior aerodynamic efficiency at the cost of low volumetric capacity, while lifting bodies sacrifice partial aerodynamic performance for enlarged internal space. The final configuration selection depends on the core requirements of specific flight missions.

7. Conclusion

This paper reorganizes all knowledge points from the aerospace engineering course in teaching order, progressing from incompressible fluid fundamentals, viscous numerical methods, compressible shock waves and jet engine cycles, to rocket orbital mechanics and hypersonic re-entry theories. According to lecture content, Reynolds number controls viscous low-speed flow while Mach number determines compressible high-speed flow; potential flow theories taught in tutorials

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can predict ideal lift, whereas boundary layer viscosity and shock wave loss are the two main sources of flight drag. Jet engines work by taking in air from the atmosphere, whereas rockets produce thrust only by ejecting stored propellant, and all orbital design in space lessons takes velocity increment ΔV as the core design standard. The whole subject forms a complete logic chain from low-speed aircraft to deep-space rockets, which is hidden in separated course chapters.

However, all theories learned from courses are based on ideal gas and steady atmospheric assumptions, while ignoring unsteady flow, unstable combustion and real gas effects. For further study after this course, students can use high-precision CFD simulations to check theoretical results, and analyze modern reusable spacecraft with the knowledge gained from this module.

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