Proceedings of the 3rd International Conference on Computing Innovation and Applied Physics
DOI: 10.54254/2753-8818/9/20240759

Analysis of the pneumatics principles of several aircrafts

Shiyi Zhan

Xi'an University of Science and Technology, Xi'an , Shanxi, China, 710054

2206757134@qq.com

Abstract. In recent years, the advancement of science and technology, particularly the development of flight control technology, has driven the progress of aircraft technology, which facilitates the rapid development of many kinds of aircraft. Pneumatics, the mechanics of gas flow, is used to study aerodynamics. In the design and manufacturing of aircraft, gas flow has a significant impact on the movement, control, attitude, stability, and other aspects of the aircraft. This paper describes the basic Pneumatics principles in aircraft design: aerodynamics is the discipline that studies the interaction between airflow and aircraft, it is the core foundation of aircraft external shape design, a pivotal discipline in overall design, and a prerequisite for conducting design analyses in fields, it plays a crucial role in aircraft design and force analysis for the aircraft, and this paper also introduces the aerodynamic layout design and aerodynamic characteristics of tilt-rotor Unmanned Aerial Vehicle (UAV), multi-rotor aircraft and bionic flapping wing aircraft, so as to offer some references for future study of air vehicles.

Keywords: Aerodynamics, Tilt-Rotor Unmanned Aerial Vehicle, Multi-Rotor Aircraft, Biomimetic Flapping Wing Aircraft.

1. Introduction

With the changing landscape of internationalization, aviation development has surged rapidly, accompanied by an increasing level of informatization. Aviation technology is also facing numerous new challenges, placing higher demands on its capabilities. Among the fundamental disciplines of aviation technology, aerodynamics, which stands as one of the cornerstones, is similarly confronted with a host of novel challenges and opportunities. Concurrently, aerodynamics is one of the fundamental scientific disciplines underlying aerospace technology, playing an irreplaceable role in national security, economic advancement, and social stability. In aircraft design, the principles of aerodynamics play a pivotal role. To engineer aircraft with superior flight performance, an in-depth understanding and mastery of aerodynamic principles are indispensable.

Aerodynamics pertains to the study of the behavior of air and the dynamics associated with it, encompassing the mechanics of gas flow. Within aircraft design and manufacturing, the flow of gases profoundly influences various aspects such as the aircraft's motion, control, attitude, and stability. This paper expounds upon the fundamental principles of aerodynamics in aircraft design and presents the aerodynamic layout design and characteristics of three types of aircraft: tilt-rotor unmanned drones, multi-rotor aircraft, and biomimetic flapping-wing aircraft.

DOI: 10.54254/2753-8818/9/20240759

2. Aerodynamic principles in aircraft design

Aircraft overall design is the process of comprehensively and coherently researching and designing the aircraft and its various systems based on specified requirements, involving multiple disciplines and fields of expertise [1].

Aerodynamics is the discipline that studies the interaction between airflow and aircraft. The aerodynamic performance of an aircraft is influenced by the flow of air, and the flow and mechanical properties of air are determined by vortices and aerodynamic principles. Aerodynamic principles encompass multiple aspects such as airflow, aerodynamic characteristics, and flight dynamics. Among these, airflow serves as a fundamental basis for aircraft aerodynamics, involving concepts like flow, boundary layer, and turbulence. Aerodynamic characteristics involve essential concepts such as lift, drag, lift-to-drag ratio, and aerodynamic center. Flight dynamics integrates the interaction between the aircraft and the air, investigating aspects like flight conditions, stability, and maneuverability.

Aircraft aerodynamic issues in design primarily fall into two categories: first, the aerodynamic forces generated by the air acting on the aircraft during flight, including aerodynamic drag, lift, lateral forces, and rolling moments; second, force analysis and dynamic strength analysis during the design phase.

First and foremost, aerodynamics plays a crucial role in aircraft design. The lift of an aircraft mainly stems from the lift generated by the airfoil and the inclined pressure on the aircraft body, where the lift from the airfoil is a result of the flow around the wing and the pressure distribution on the wing surface. Through aerodynamic analysis, suitable airfoil shapes and aircraft attitudes for different missions can be designed, along with the placement of control devices. Additionally, aircraft generate significant aerodynamic forces during flight, such as aerodynamic drag, lift, initial side forces, and fore-aft stability forces. Therefore, aerodynamic research for aircraft plays a significant role in longitudinal and lateral flight control. For instance, designing different forms of tail fins and stabilizers can achieve longitudinal and lateral control for unmanned drones.

Secondly, aerodynamics also has an indispensable role in force analysis for aircraft. Force analysis is crucial in aircraft design, and aerodynamics plays a vital role in this analysis. When conducting force analysis, one must consider the aerodynamic forces produced by gas flow as well as the aircraft's response to gas flow. Simultaneously, the interaction between the aircraft and the air, including thermal-structural interaction and dynamic strength analysis, should also be considered.

The specific process of force analysis involves analyzing and calculating the various forces acting on the aircraft to determine their impact. In aircraft force analysis, aerodynamics provides essential parameters like aerodynamic coefficients and flow field characteristic parameters. These parameters can be used to optimize aircraft design and alter aircraft performance.

In summary, aerodynamics in aircraft design involves not only the study of fundamental theories but also the comprehensive consideration of various design factors. Aerodynamics is the core foundation of aircraft external shape design, a pivotal discipline in overall design, and a prerequisite for conducting design analyses in fields such as trajectory, payload, and attitude control. In engineering design, aircraft aerodynamic shapes are often based on existing forms, adjusted by manipulating shape parameters, analyzing aerodynamic data (using engineering algorithms or CFD calculations), and undergoing multiple rounds of iteration to achieve a shape that meets design requirements [2].

3. Aerodynamic layout design and characteristics of tilt-rotor UAVs

Tilt-rotor aircraft is a type of aircraft that combines the advantages of both fixed-wing airplanes and helicopters, offering a variable flight mode. Compared to fixed-wing airplanes, tilt-rotors can perform vertical takeoff and landing, require less runway, and exhibit better adaptability to various terrains. In contrast to conventional helicopters, tilt-rotors boast higher cruise speeds, extended ranges, reduced vibrations, lower fuel consumption, and increased payload capacity [3]. Furthermore, when compared to both helicopters and fixed-wing aircraft, tilt-rotor aircraft possess a wider flight envelope [4].

DOI: 10.54254/2753-8818/9/20240759

3.1. General design

Due to the different flight modes of tilt-rotor unmanned drones, various flight states must be considered during the overall design phase. TyanMaxim [5] designed a vertical takeoff and landing fixed-wing unmanned drone, estimating the propulsion system's mass for vertical takeoff and forward flight modes separately using empirical formulas in the mass estimation of overall design. Zhu Qingzhen [6] selected hover efficiency in tilt-rotor helicopter mode and equivalent productivity in fixed-wing mode as objective functions, employing an colony algorithm to optimize overall parameters such as total weight and wing area.

Complex aerodynamic interference exists between the rotor, wings, and fuselage of tilt-rotor unmanned drones. This interference is highly nonlinear and unsteady, causing unpredictable aerodynamic loads on the aircraft during flight missions. The tilt mechanism is usually installed at the wingtip or extended ahead of the wing. When installed at the wingtip, the rotor downwash affects the wing, generating downward aerodynamic loads in helicopter mode and thereby reducing the effective payload. During tilt, dynamic airflow over the wing continues, affecting the aircraft's stability and controllability. Therefore, an appropriate layout is necessary during the design phase to mitigate the impact of aerodynamic interference. When the tilt mechanism is extended ahead of the wing, rotor airflow can effectively avoid impacting the wing in helicopter and transition modes. In fixed-wing mode, the rotor's impact is similar to that of a propeller. The layout design of tilt-rotor unmanned drones' tilt mechanisms often involves extending the wing.

In terms of structural design, the tilt mechanism bears different rotor forces in various flight modes, necessitating increased structural strength. When considering lateral rotor layout, increasing the distance between rotors can enhance control authority, but it simultaneously increases the drone's moment of inertia, requiring higher wing structural strength. In the design phase, finding a reasonable position for the tilt mechanism is crucial.

3.2. Aerodynamic analysis

Accurate aerodynamic analysis of tilt-rotor drones forms the foundation for predicting their flight performance. Additionally, it provides essential aerodynamic data for the design of controllers for tilt-rotor aircraft. Aerodynamic models for fixed-wing aircraft, such as lift-line models, lifting-surface models, and three-dimensional panel models, have reached a mature and accurate stage. However, aerodynamic models for rotor craft and rotor/wing aerodynamic interference models are still under development.

For rotor aerodynamics analysis, the simplest model is the classic momentum theory or the actuator disk model. This model treats the rotor as an infinitely thin plane that pressurizes and accelerates the fluid passing through the plane of the rotor disk, neglecting the geometric shape of rotor blades and flow details. It assumes incompressible and inviscid fluid and ignores rotor rotation. The actuator disk model can only estimate rotor thrust and is less accurate for design and analysis purposes. Subsequently, momentum theories considering rotor rotation, blade element theories that consider blade geometry while neglecting induced velocity, and Blade Element-Momentum Theory (BEMT) that considers induced velocity were successively proposed. Additionally, vortex models are used to handle induced velocity in blade element theory.

All the above-mentioned models describe the case of axial inflow without an angle of attack. Researchers have also proposed corresponding models for cases with angle of attack and forward flight speed. In recent years, various modifications and new issues have been introduced for the actuator disk model. For instance, modifications involving edge singularities include discretely distributed edge forces to address issues like the interaction between rotor blade elements' vortices that remain unaccounted for. Simplified aerodynamic models for rotors also include the Free Wake Method, which originates from the trailing vortex lines of the rotor, as depicted in Figure 1. This method also requires fewer computational resources but is less applicable to transonic and unsteady flow problems.

DOI: 10.54254/2753-8818/9/20240759

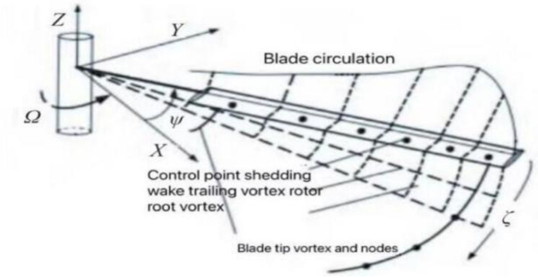

Figure 1. Free wake analysis of rotor aerodynamics using the vortex lattice method.

As research progresses, the considerations for models become increasingly complex, leading to more intricate processing and calculations. Employing Computational Fluid Dynamics (CFD) for analyzing the three-dimensional flow field of rotors, while incurring higher computational costs, yields more precise results and provides a more detailed representation of the flow field information.

When analyzing the aerodynamic characteristics of rotor tilt processes, the CFD method can be utilized to compute the three-dimensional dynamic flow field. The simplest model involves utilizing the actuator disk theory, which simplifies the rotor into a fixed-thickness mesh, calculating the motion and source terms of each grid at every moment. This approach is referred to as the momentum source method. Alternatively, a more detailed approach involves constructing an actual body-fitted mesh model of the rotor to capture finer surface flow dynamics. A hybrid rotor model, employs the momentum source method-calculated flow field as the initial background flow field of the real rotor model, followed by iterative CFD calculations. This method converges more rapidly and can save approximately one-third of the computational costs.

Concerning dynamic flow field analysis, in addition to methods like the free wake method and dynamic mesh and overlapping grid techniques within the CFD approach, there's an analytical method that involves coupling Computational Fluid Dynamics with Multi-Body Dynamics (MBD). The CFD/MBD coupled analysis method addresses the limitations of traditional CFD methods that maintain a fixed position and attitude of the unmanned aircraft within the flow field grid. In each iterative step, the CFD/MBD method updates both the motion information and aerodynamic force information, thereby enhancing accuracy and real-world relevance.

4. Aerodynamic layout design of multi-rotor aircraft

In recent years, the advancement of science and technology, particularly the development of flight control technology, has driven the progress of multi-rotor aircraft technology. This progress has facilitated the rapid development of micro-sized multi-rotor aircraft. In real-world applications, large payload multi-rotor aircraft have found utility due to their advantages of simplicity in operation and flight stability. However, due to the high-speed motion of rotors, there is a propensity for rigid rotor blades to break through repeated contact with the rotor hub. Electric multi-rotor aircraft, on the other hand, face limitations in payload enhancement due to issues with motor and electronic speed controller (ESC) technologies, resulting in inadequate thrust.

While internal combustion engine-powered multi-rotor aircraft have ample power, they often exhibit slow response times, leading to challenges in control response and limiting their widespread use in multi-rotor applications. This paper compiles and summarizes common aerodynamic configurations of multi-rotor aircraft and analyzes their respective advantages and disadvantages.

4.1. Dual-rotor aircraft

As a current research hotspot, coaxial rotor aircraft generate lift through the rotation of two sets of rotors - one rotating in the opposite direction to the other. The counter-rotating rotors produce lift while counteracting each other's torque, and a differential collective pitch between the upper and lower rotors

DOI: 10.54254/2753-8818/9/20240759

generates yaw control. The rotor system serves both as the lifting surface and the control surface, eliminating the need for a tail rotor and achieving relatively high hover efficiency [7].

One of its main advantages is the absence of a tail rotor, leading to a comparatively shorter fuselage. The longitudinal dimensions are only 60% of those of traditional helicopters, resulting in a smaller overall size. This design eliminates the potential failure risks associated with traditional tail rotors and the problems stemming from tail boom vibrations or deformations. Furthermore, the structural weight and payload are concentrated at the center, reducing pitch and yaw inertia. A significant drawback, however, lies in the increased longitudinal dimensions due to the upper and lower rotor configuration. Additionally, the rotor system increases the parasite drag area, resulting in higher parasite power compared to traditional helicopters. The transmission and control mechanisms of coaxial dual rotors are also relatively complex. The rotor structure is notably intricate, leading to complex aerodynamic characteristics. Furthermore, due to the close proximity of the upper and lower rotors, the rotor vortices can induce interference with each other, resulting in pronounced aerodynamic disturbance phenomena.

4.2. *Tri-rotor aircraft*

In recent years, compared to quad-copter aircraft, tricopter aircraft have been relatively uncommon. Tricopter drones typically adopt a Y3 configuration. Due to the reduced number of rotors compared to quad-copters, tricopters possess advantages such as simpler and more compact structure, lower energy consumption, lighter weight, better endurance, improved maneuverability, and greater flexibility. However, since the torque generated by the three rotors in a tricopter configuration is not as easily balanced as in a quad-copter configuration, the control system is more complex, and control difficulties are relatively higher and less mature. As a result, the layout of tricopter aircraft presents significant challenges, and its practical application is very rare.

4.3. *Quad-rotor aircraft*

A quad-copter aircraft features four rotors arranged in either a cross-shaped or X-shaped distribution. The adjacent rotors rotate in opposite directions, and by employing counter-rotating propellers, the reactive torque can be balanced, resulting in stability. Quad-copter flight control is primarily achieved by adjusting the rotor speeds of the four motors, which, in turn, changes the lift produced by the rotors [8]. The key advantages of quad-copter aircraft include vertical takeoff and landing capabilities, as well as stationary hovering. They boast a simple structure, excellent stability, innovative design, high cost-effectiveness, strong hovering capabilities, and good maneuverability. Some of the main drawbacks are their relatively lower efficiency and limited flight attitudes compared to helicopters.

Quad-copters have consistently been a subject of research for scientists and engineers worldwide and are among the most widely used types of aircraft today. The research on this aerodynamic layout, both domestically and internationally, mostly pertains to small unmanned aerial vehicles (UAVs) where the technology has become quite mature. China, in particular, holds over 80% of the market share in this field, making it the global leader in quad-copter technology for small UAVs.

5. Aerodynamic principles of biomimetic flapping-wing aircraft

Biomimetic flapping-wing aircraft are a new type of aircraft developed based on the flight characteristics of birds and insects. They utilize the aerodynamic lift and thrust generated by the flapping motion of two wings to aid in ascent and forward movement. Flapping-wing aircraft possess high agility, stealth capabilities, and aerodynamic efficiency. By autonomously controlling their flight, they can assist in tasks that are currently beyond human capability, providing convenience to society. However, due to the complex motion patterns and aerodynamic mechanisms of flapping flight not yet being fully understood, research and development in this field hold vast potential.

Flapping-wing flight offers several advantages [9]: (1) Simplicity: Flapping flight is a straightforward way of generating the necessary thrust and lift using the up-and-down motion of dual wings, making it a simple and efficient mode of flight. (2) Flexibility: Flapping flight is highly adaptable, requiring minimal space for takeoff and landing and allowing operation in confined areas. (3) Maneuverability: Flapping flight exhibits excellent maneuverability, adapting well to various flight environments. Flight speed can be adjusted by altering flapping amplitude and frequency, while yaw control is achieved through lateral tail wing movement. (4) Efficiency: Flapping flight boasts high efficiency and low energy consumption due to its unique lift mechanism, typically avoiding stall conditions.

The notable advantages of flapping-wing aircraft have led to widespread applications in both military and civilian domains. In the military sector, they are utilized for low-altitude reconnaissance, image capture, electronic countermeasures, precision delivery, and more. For instance, using flapping-wing aircraft for reconnaissance can effectively mitigate casualties and enemy traps. Equipped with specialized devices, flapping-wing aircraft can even gather audiovisual intelligence, carry out targeted assassination missions, and eliminate enemy facilities. In the civilian sector, they are employed for tasks like monitoring natural disasters and environmental pollution. Despite the challenging research path and setbacks, scientists and researchers have never ceased exploring and studying the realm of flapping-wing flight.

6. Conclusion

With the development of aerospace, aerodynamics has gradually become the fundamental science for the development of aerospace technology. From the invention of the Wright brothers to the flying of the F-22 in the vast sky, it can be seen that global aircraft research and manufacturing are linked to aerodynamics research, and the relationship between aerodynamics and the aviation industry is inseparable. Even though aerodynamics faces many challenges, it is also needed by people. It is believed that the future aviation industry will make greater progress under the guidance of aerodynamics, and the aviation industry will make greater contributions to the economic construction and national security of the entire society, making the world's sky more colorful and making our lives full of vitality.

References

[1] Hou S. Aircraft overall design and testing [M] Beijing: Astronautic Publishing House, 1996.
[2] Chi Y., Zhang Y., Zheng X., etc. Rthogonal design and analysis of aircraft aerodynamic shape [J]. aerospace overall technology, 2022, 6(1): 51-53.
[3] Chen H. Unsteady aerodynamic numerical simulation of tilt-rotor aircraft in transition mode [D]. Nanjing: Nanjing University of Aeronautics and Astronautics, 2018.
[4] Zuo Z. Selection and design optimization of tilt-rotor aircraft overall parameters [D] Nanjing: Nanjing University of Aeronautics and Astronautics, 2017.
[5] Tyan M., Nguyen N.V., Kim S., et al. Comprehensive preliminary sizing/resizing method for a fixed wing-VTOL electric UAV [J]. Aerospace Science and Technology, 2017, 71: 30-41.
[6] Zhu Q.Z. Optimization of tilt-rotor aircraft overall parameters [D]. Nanjing: Nanjing University of Aeronautics and Astronautics, 2011.
[7] Chen M. Aviation manufacturing technology technical features and development of coaxial dual-rotor helicopters [J] 2009, (17): 26-31.
[8] Carrillo LRG., López AED., Lozano R., et al. Quad Rotorcraft Control [M]. Springer London, 2014.
[9] Xiu X. Biomimetic flapping-wing aircraft mechanism design and simulation [D] Mianyang: Southwest University of Science and Technology, 2017.