Chapter 2
Aircraft Performance and Design

> *It is possible to fly without motors, but not without knowledge and skill*
>
> —Orville Wright

This Chapter reviews the fundamental principles of aerodynamics and flight dynamics of fixed-wing aircraft. It also includes the challenges of modeling of a pusher inverted V-tail twin boom fixed wing configuration and the performance characteristics of such designs.

2.1 Design Considerations

2.1.1 Wing Design

The wing is the most important component of a fixed-wing aircraft, since the aircraft cannot fly without it. The wing geometry influences all other aircraft components; thus, the aircraft design process begins from the wing. The primary function of the wing is to generate a sufficient lift force (L). However, the wing also creates drag force or drag (D) and nose-down pitching moment (M). The ultimate goal of an aerodynamicist is to maximize lift while minimizing drag and pitching moment [6]. To achieve sufficient lift while generating minimum drag and minimum pitching moment, according to Sadraey [6], there are 22 design parameters of the wing that need to be investigated. Design goals must be collectively satisfied throughout all flight operations and missions. The design parameters are:

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i Wing reference (or planform) area (SW or Sref or S)
ii Number of the wings
iii Vertical position relative to the fuselage (high, mid, or low wing)
iv Horizontal position relative to the fuselage
v Cross section (or airfoil)
vi Aspect ratio (AR)
vii Taper ratio
viii Tip chord (Ct)
ix Root chord (Cr)
x Mean Aerodynamic Chord (MAC or C)
xi Span (b)
xii Twist angle (or washout)
xiii Sweep angle (β)
xiv Dihedral angle (Λ)
xv Incidence (iw) (or setting angle, set)
xvi High lifting devices such as flap
xvii Aileron
xviii Wing tip
xix Winglets
xx Fairing
xxi Vortex generator
xxii Other wing accessories

After the wing surface area is defined, the number of wings is chosen. More than three wings is impractical, and it is true that modern aircraft (manufacture advance) and UAVs are monoplane. The argument that two wings have more surface than a single wing may not stand today, since technology has improved and the manufacturing techniques and the use of strong and lightweight materials allow for the design of longer wings since the ability to structurally support to stay level and rigid is feasible.

The wing location relative to the fuselage's centerline is a parameter that influences the aircraft tail design, the landing gear, and the center of gravity. There are four possible locations: high-wing, mid-wing, low-wing, and parasol-wing. Cargo aircraft have mostly high-wing, while most passenger aircraft have low-wing. On the other hand, most fighter airplanes have mid-wing, while hang gliders and most amphibian aircraft have parasol-wing. Most UAVs and RC planes have high-wing configurations because the main criterion is producibility and assemble-ease. High wing seems to be the best candidate for the sample problem and UAV applications. A high-wing configuration does not fully satisfy all design requirements, but it is an optimum option given the fact that allows for more space in the fuselage for payload and its simplicity to be integrated on the fuselage.

The most important parameter after the wing area is defined, is the airfoil selection/design. As it is stated earlier, the primary function of the wing is to generate lift, which will be generated by a special wing cross section, called airfoil. The airfoil design is a complex procedure and requires a high level of aerodynamics knowledge and expertise. After the design process, the airfoil needs to be verified through wind tunnel testing, and that process is also expensive. UAV companies do not design their own airfoils but, instead, they select the best airfoils among the current available airfoils that are found in several books or websites and if there are slight modifications, they use CFD tools to verify the performance. CFD codes reduce the amount of required wind tunnel testing and allow for airfoils to be tailored to each specific application. Aerodynamics textbooks introduce theories to analyze flow around an airfoil [7, 8]. One of the oldest and most reliable airfoil designers is Richard Eppler in Germany [9], who has developed an airfoil design code that is based on conformal mapping. Any section of the wing cut by a plane parallel to the aircraft xz plane is called an airfoil. A typical airfoil section is shown in Fig. 2.1, where several geometric parameters are illustrated. When the mean camber line is a straight line, the airfoil is referred to as symmetric airfoil, otherwise it is called cambered airfoil.

Accurate predictions of lift, drag, and pitching moment are critical for the design and performance evaluation of airfoils. Wind tunnel testing is also a key component of the design process, as it complements CFD and other prediction tools. The aerodynamic force generated by an airfoil in a flow field may be calculated by multiplication of total pressure by area (integration of pressure over the entire surface). An electronic pressure scanning system (EPS) is used to measure accurately the pressure at different locations along the airfoil's chord. The total pressure is determined by integration of pressure over the entire surface. The magnitude, location, and direction of this aerodynamic force (total pressure) are functions of airfoil geometry, angle of attack, flow property, and airspeed relative to the airfoil [6]. The exact location of the resultant force out of the integration, which depends on the aircraft's speed and angle of attack, is called center of pressure (cp). At low speeds, the center of pressure is closer to the leading edge while higher speeds it moves toward the trailing edge of the wing. Determining the aerodynamic behavior of an airfoil is complicated if the center of pressure is used to analyze the forces since the pressure distribution changes; this causes the aerodynamic force, the location of the center of pressure and

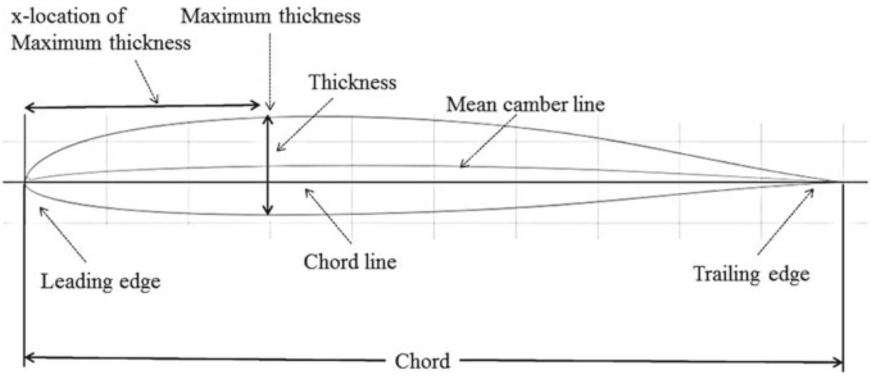

Fig. 2.1 NACA 2412 airfoil parameters

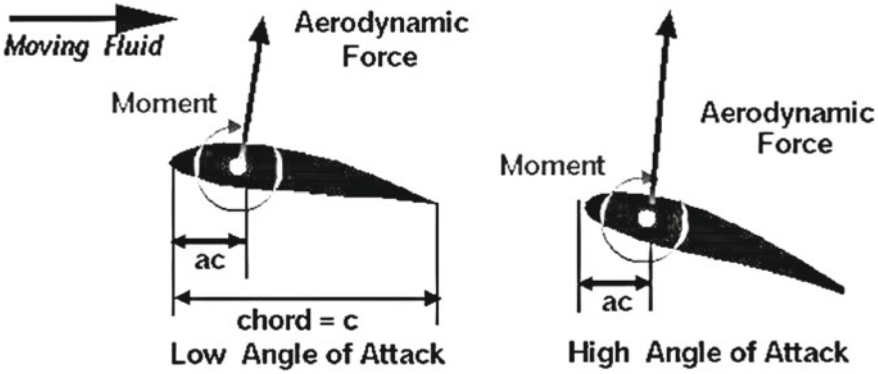

Fig. 2.2 Pitching moment and aerodynamic center

the moment to change. One may compute the moment about any point on the airfoil if the pressure distribution is known. The aerodynamic force will be the same, but the value of the moment will depend on the point where that force is applied. It has been found both experimentally and theoretically that if the aerodynamic force is applied at a location 1/4 chord back from the leading edge on most low-speed airfoils, the magnitude of the aerodynamic moment remains nearly constant with angle of attack [7, 8]. The force and moment on a wing can be completely specified by the lift and drag acting through the aerodynamic center, plus the moment about the aerodynamic center (Fig. 2.2). An external or internal force balance is used to measure the forces and moments applied on the airfoil in a wind tunnel environment. The pressure and shear stress distributions over a wing produce a pitching moment. This moment can be taken about the leading edge, the trailing edge, or the quarter chord.

Another parameter, which is related to the wing design, is the wing incidence. The wing incidence (iw) is the angle between fuselage center line and the wing chord line at root and it can be chosen to be variable or constant during flight.

The variable wing incidence is not recommended, since there are safety and operational concerns. Instead, a constant wing setting angle is preferred, since it is safer when compared with variable setting angles. However, the designer must determine the angle at which the wing is attached to the fuselage so the wing is able to generate the desired lift coefficient during cruise flight, while producing minimum drag. Also, the wing setting angle must be such that the wing angle of attack could be safely varied during takeoff so the fuselage generates minimum drag during cruise flight.

2.1.2 Aircraft Tail Design

An aircraft is a dynamic system that is used for, or is intended to be used for, flight in the air. The major categories of aircraft are airplane, glider, rotorcraft, and lighterthan-air vehicles. The most common aircraft type is the fixed-wing configuration, where the wings are attached to the fuselage and are not intended to move independently in a way that results in the creating lift [7, 8]. The fundamental aircraft parameters that need to be considered at the first design phase are the maximum takeoff weight (MTOW), the wing reference area and the engine thrust/power. These parameters are critical for the aircraft design and govern size, cost, and calculation complexity.

The design and shape of the aircraft tail is an important task since it influences the control power of the aircraft. A large variety of tail shapes have been investigated and employed over the years; they are denoted by the letters whose shapes they resemble in front view: T, V, inverted V, H, +, and Y. The selection of the particular configuration involves complex system-level considerations, since the mathematical model of the aircraft changes significantly. Tail surfaces are used to both stabilize the aircraft and provide control moments needed for maneuver and trim [7, 8]. Because these surfaces add wetted area (increase drag) and structural weight, they are often sized to be as small as possible. However, in some cases this is not optimal and the tail is generally sized based on the required control power. An example is the conventional configuration with the low horizontal tail, where both horizontal and vertical root surfaces are conveniently attached directly to the fuselage; in this case the effectiveness of the vertical tail is large because of its interference with the fuselage, while the horizontal tail increases its effective aspect ratio. It is true that large areas of the tail are affected by the converging fuselage flow but in some cases, it can reduce the local dynamic pressure.

The tail in conventional aircraft has often two components of horizontal and vertical tail with their functions being longitudinal and directional: trim, stability, and control. Longitudinal trim in a conventional aircraft is applied through the horizontal tail. Trim is not a major function for vertical tail, since conventional aircraft are almost always manufactured symmetrically about the xz plane, but, in some cases, vertical tail has the primary function of directional trim or lateral trim. Regarding longitudinal and directional stability, the horizontal tail is responsible to maintain the longitudinal stability, while the vertical tail is responsible to maintain the directional stability. Finally, when it comes to *control*, the elevator (part of the horizontal tail) is designed to provide longitudinal control, while the rudder (part of the vertical tail) is responsible to provide the directional control. The tail must be able to control the aircraft during change of the flight conditions from level flight to takeoff/landing. For instance, during takeoff, the tail must be able to lift up the aircraft nose in a specified pitch rate [6].

A T-tail is often chosen to move the horizontal tail away from the engine exhaust and to reduce aerodynamic interference, while H-tails use the vertical surfaces as endplates for the horizontal tail, increasing its effective aspect ratio. Y-shaped tails have been used on propeller aircraft, where the downward projecting vertical surface serve to protect a pusher propeller from ground strikes. A disadvantage using a Y-tail configuration is that it limits takeoff/landing pitch angles. Inverted V-tails have some of the same features and problems with ground clearance, while producing favorable rolling moments with yaw control input. V-tails combine functions of

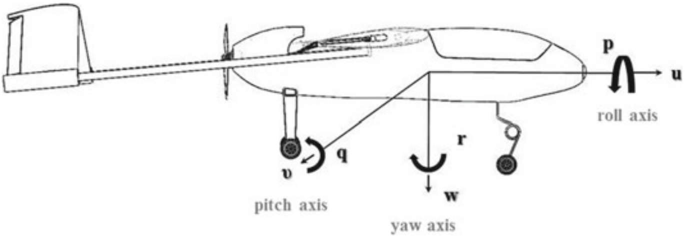

Fig. 2.3 Axes of rotation (roll-pitch-yaw) of a fixed-wing aircraft

horizontal and vertical tails. They are sometimes chosen because of their increased ground clearance, reduced number of surface intersections, but may require mixing of rudder and elevator controls and often exhibit reduced control authority in combined yaw and pitch maneuvers.

The main advantage of the inverted V-tail when in use with twin boom aircraft design is its structure rigidity. Comparing V-tail and inverted V-tail UAV configurations, there is not much of a difference when it comes to calculation and dynamics/modeling. However, an inverted V-tail aircraft (Fig. 2.3) is slightly better for yaw control in coordinated turn (inverted V provides some pro-verse yaw). If the elevons are correctly sized and set the v-angle correctly, coordinated turns with little or no aileron are possible. Also, in favor of inverted V-tail designs is the UAV's stability in cross wind situations, when hit by a cross wind gust on landing the inverted V will cause the airplane to pitch up as opposed to diving into the ground. However, that will make a difference when the aircraft is remotely piloted and not if an autopilot is used on-board.

2.2 Remarks

This Chapter reviewed the fundamental principles of aerodynamics and flight dynamics of fixed-wing aircraft. From wing to tail, it presented the challenges of modeling and design of a pusher inverted V-tail twin boom fixed-wing configuration and the performance characteristics of such designs.

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