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Aircraft Components and Subsystems

This chapter deals with the fundamental physical components and properties of conventional fixed-wing aircraft. This material is covered in detail in many textbooks (see Anderson [1998, 2000], Asselin [1997], Eshelby [2000], Layton [1988], Lowry [1999], Mair and Birdsall [1996], Roskam and Lan [1997], Saarias [2006], Shevell [1988], Torenbeek and Wittenberg [2009], and Yechout and Bossert [2003]); see Collinson (1996) for an overview that also describes flight instruments and avionics. The treatment here is brief and emphasis is given to the aspects of conventional aircraft that are most related to their flight characteristics.

1.1 Aircraft Subsystems for Conventional Fixed-Wing Aircraft

Figure 1.1 illustrates a conventional fixed-wing aircraft that is the basic flight vehicle of interest in this book. The key physical components, or subsystems, that define the aircraft are the fuselage, the wings, the horizontal tail, the vertical tail, and the propulsion system. The fuselage provides working volume for passengers, cargo, and aircraft subsystems that are internal to the aircraft. The fuselage is important in terms of achieving particular flight missions, but it is not especially important from a flight performance perspective. The two wings are crucial for flight, since their main purpose is to generate lift. The aircraft illustrated in Figure 1.1, and all aircraft considered hereafter, are fixed-wing aircraft, since the wings are rigidly attached to the fuselage. This is in contrast with helicopters or other rotary wing flight vehicles that generate lift using rotating blades.

Other important flight subsystems, illustrated in Figure 1.1, are the horizontal tail, the vertical tail, and the engines. The horizontal and vertical tails are rigidly attached to the fuselage as indicated. The horizontal tail provides longitudinal stability and control capability, while the vertical tail provides directional stability and control capability. The engines are crucial flight subsystems, since they generate the thrust force that acts on the aircraft. Note that gliding flight, studied in chapter 6, occurs if the engines are turned off so that they do not generate thrust; gliders have no propulsion system.

The above descriptions imply that the aircraft can be viewed as a rigid body, and this is the perspective that is taken throughout. That is, there is no relative motion between the physical aircraft subsystems such as the fuselage, the wings, and the vertical and horizontal

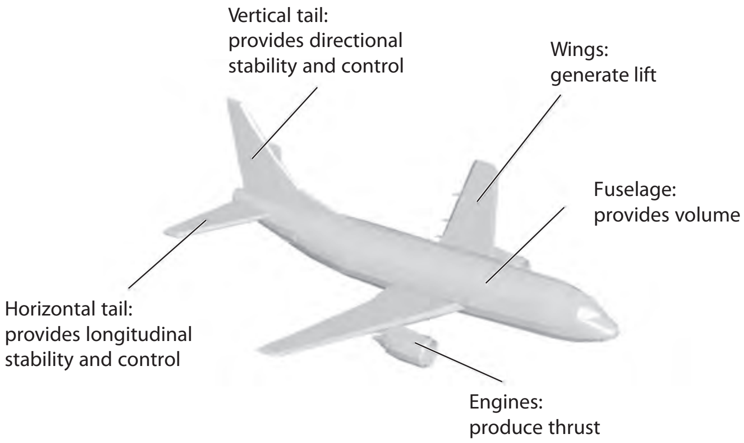

Figure 1.1. *Aircraft subsystems.*

tails. Since many forces act on these physical subsystems, the rigid body assumption is only a crude approximation. In fact, the aircraft physical structures deform under the applied forces that occur during flight. Issues of structural design and analysis are important to guarantee that the rigid body assumption is justified.

This is the appropriate point to mention another important assumption that holds throughout the analysis presented subsequently. The complete aircraft, consisting of the fuselage, the wings, the horizontal and vertical tails, and all other flight subsystems, has a plane of mass symmetry that exactly bisects the aircraft. This assumption is a consequence of the design of conventional fixed-wing aircraft where, in particular, engines mounted on the fuselage or the wings are balanced to satisfy this mass symmetry assumption.

1.2 Aerodynamic Control Surfaces

Figure 1.2 illustrates three types of aerodynamic control surfaces: the elevator, the ailerons, and the rudder. The elevator is one (or more than one) movable flap, located on the trailing edge of the horizontal tail. Deflection of the elevator changes the air flow over the horizontal tail in such a way that a pitch moment on the aircraft is generated. The ailerons consist of a pair of movable flaps, located on the trailing edge of each wing; ailerons usually operate in differential mode so that if one flap is deflected up the other flap is deflected down by the same amount or vice versa. Differential deflection of the ailerons changes the air flow over the wings in such a way that a roll moment on the aircraft is generated. The rudder is one (or more than one) movable flap, located on the trailing edge of the vertical tail. Deflection of the rudder changes the air flow over the vertical tail in such a way that a yaw moment on the aircraft is generated. The elevator deflection, rudder deflection, and the differential deflection of the ailerons are typically viewed as angles measured from some reference values.

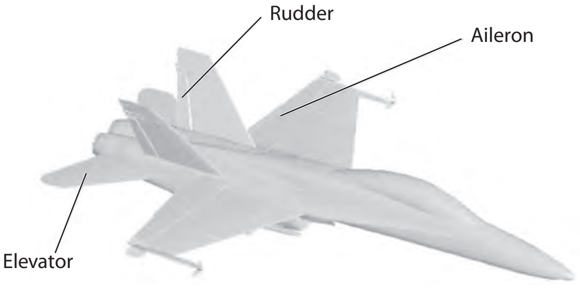

Figure 1.2. *Aerodynamic control surfaces.*

These movable flaps are referred to as aerodynamic control surfaces; they generate moments on the aircraft according to the principles of aerodynamics. The precise meanings of pitch, roll, and yaw moments are described later. These moments are used to maneuver and control the flight of the aircraft.

Some modern aircraft have unconventional elevators, ailerons, and rudders, as well as additional flaps on the fuselage referred to as canards. Although many aerodynamic control surface designs are possible, they all are intended to generate pitch, roll, and yaw moments. The subsequent development in this book is based on the assumption that conventional elevators, ailerons, and rudders are utilized.

1.3 Aircraft Propulsion Systems

The aircraft engines, together with associated fuel tanks and related hardware, are referred to as propulsion systems. The purpose of the propulsion system is to generate a thrust force that propels the aircraft in flight. Although engines and propulsion systems are extremely complicated, detailed knowledge of the engine specifications is not required to analyze flight properties of an aircraft. Rather, the key features for the study of steady flight are the maximum thrust (or the maximum power) that the engine can produce and the rate at which fuel is burned to produce a given thrust level (or power level).

From the earliest days of powered flight, propulsion systems have consisted of an internal combustion engine that causes rotation of a propeller. The blades of the propeller are designed so that they generate a thrust force. Such propulsion systems remain in common use today, especially for low-speed aircraft for which cost and durability considerations are primary. The important specifications for this type of propulsion system are the maximum power that the internal combustion engine can produce, the rate of fuel burned to provide a specified power level, and the efficiency of the propeller.

An important technological outcome of World War II was the development of jet engine technology. Such propulsion systems make high-speed flight possible. Most jet engines consist of a compressor, a turbine, and a combustor that are used to accelerate the flow of air through the engine, thereby producing a thrust force on the aircraft. These turbojet engines are extremely complicated, but the important specifications are the maximum thrust that the turbojet engine can produce and the rate of fuel burned to provide a specified thrust level.

Turboprop engines use turbine and jet engine technologies to turn a propeller that generates a thrust force on the aircraft. These propulsion systems exhibit some of the features of conventional jet engines, but the efficiency of the propeller is also important.

Finally, rocket engines have been used to generate propulsive thrust forces on certain experimental aircraft. A rocket engine consists of fuel and an oxidizer that are stored internally in the aircraft; as the fuel is burned the combustion products are exhausted out a nozzle to produce a thrust force on the aircraft. Rocket engines can generate extremely large levels of thrust, but they have limited duration of operation.

Our focus here is on conventional propulsion systems: either a propeller driven by an internal combustion engine or a turbojet engine. Many of the subsequent developments can be modified to handle other types of propulsion systems.

The aircraft propulsion system produces a thrust force vector that has a fixed direction with respect to the aircraft. This property arises since the engines are typically fixed in the aircraft, either on the wings or on the fuselage. The direction of the thrust vector is also assumed to lie in the plane of mass symmetry of the aircraft. Finally, it is assumed that the engine can be throttled or adjusted so that any thrust level (or power level) between zero thrust (or zero power) and maximum thrust (or maximum power) can be achieved using a throttle setting between 0 and 1.

In some modern fighter aircraft, the direction of the thrust vector, with respect to the aircraft, can be adjusted within limits; this feature is referred to as thrust vectoring. The advantage of thrust vectoring is that control moments due to the thrust can be generated; this extra control capability can add to the maneuvering capability that can be achieved using conventional aerodynamic control surfaces. In certain flight conditions, such as post-stall flight, the aerodynamic control surfaces may be ineffective; in such cases thrust vectoring is essential to maintain maneuvering capability. Thrust-vectored aircraft are not explicitly treated in this presentation, although the methods that are subsequently developed can be modified to treat thrust-vectored aircraft.

1.4 Aircraft Structural Systems

As mentioned previously, fixed-wing aircraft consist of many structural subsystems such as the wings, the fuselage, horizontal and vertical tails, and aerodynamic control surfaces, as well as additional structural subsystems for attachment of the engines and for landing gear. Each of these structural subsystems must be designed to withstand forces and moments that are due to gravity, propulsive, and aerodynamics loadings, the most important being the aerodynamic forces and moments. In particular, these structural subsystems must maintain their structural integrity and exhibit limited deformation in the presence of expected aerodynamic forces and moments. Structural issues are crucial to the design of any aircraft.

Although the details of aircraft structural design are not central to the subsequent development of aircraft steady flight and performance that are addressed here, it is important to keep them in mind. In particular, they provide the justification for the rigid body aircraft assumption. In addition, aircraft performance is significantly limited by the aerodynamic forces for which the aircraft structure is designed. This structural limitation arises most importantly in the allowed wing loading, which, as will be shown later, limits the tightness of a turn that an aircraft can safely achieve. These issues are developed in some detail in subsequent chapters on steady turning flight.

1.5 Air Data and Flight Instrumentation

Modern aircraft are complex vehicles that contain many instruments and devices that support flight. These flight instruments use extensive electronics and are referred to as the aircraft avionics. Although these instruments do not directly influence the flight performance of an aircraft, they are important instruments for measuring flight properties and flight performance. They provide useful measurements that enable the pilot to effectively fly the aircraft. The following is a brief summary of typical avionics found on many aircraft:

- An altimeter provides a pressure measurement that approximately indicates the flight altitude above sea level, based on properties of the standard atmospheric model, as developed in chapter 2.
- The airspeed indicator provides a measurement that is used to estimate the speed of the aircraft with respect to the surrounding air.
- Engine gauges provide information about the engine status, including the engine speed and the engine temperature.
- The tachometer measures either the speed of rotation of the propeller or the turbine speed in a jet engine.
- An artificial horizon, based on gyroscopic instruments, provides measurements that can be used to estimate the roll angle and pitch angle of the aircraft (see chapter 3); this provides the pilot with an Earth-fixed reference.

1.6 Guidance, Navigation, and Control

Many aircraft also include avionics that are used for guidance, navigation, and control functions. Several types of instruments are common:

- Distance measuring equipment provides an estimate of the distance of the aircraft from a ground station based on a signal received from the ground station.
- A magnetic compass is used to estimate the heading angle of an aircraft relative to magnetic north.
- Gyroscopes are used to estimate the angular velocity of the aircraft; they are often used as components of more complicated instrument packages.

- Inertial navigation systems consist of accelerometers, gyroscopes, and associated electronics that provide estimates of the attitude of the aircraft and estimates of the velocity vector and the position vector of the aircraft in an Earth-fixed reference frame; the estimates are obtained through numerical integration of the gyroscopic and the accelerometer data.

- Global Positioning System (GPS) is a satellite-based navigation system that provides extremely accurate estimates of the inertial position of an aircraft. GPS operates by determining precise measurements of the distances of the aircraft from several satellites, located at exactly known positions, using signals broadcast by those satellites; these distances are processed to estimate the position vector of the aircraft in an Earth-fixed reference frame. In some versions, GPS can also be used to estimate the aircraft attitude.

- Instrument landing systems are microwave-based or GPS-based systems that provide information to the aircraft that is used for semiautomatic or automatic landing.

1.7 Flight Control Computers

Computer systems are now a common and essential part of many modern flight vehicles. Flight computations can be carried out by embedded computer systems that are part of an integrated avionics package that performs guidance, navigation, and control functions. A flight control computer is often available that carries out computations associated with high-level planning, including routing, automatic pilots, and flight management tasks. The flight control computer often provides an interface with the flight avionics, and it is responsible for flight data displays on the flight deck in the cockpit. The flight computer system consists of both hardware and software. Flight software in many modern flight vehicles is amazingly complex. Flight computers constitute the brains of many flight vehicles, and they are often essential for flight operations.

1.8 Communication Systems

Communication functions are important for many aircraft. As indicated previously, communications are necessary for navigation functions such as distance measurement, instrument landing, and global positioning. A transponder is a radar-based system that provides positive identification of the aircraft to an air traffic controller. In addition, VHF voice radios and omnidirectional radios allow the aircraft pilot to communicate directly with the ground and with other aircraft.

1.9 Aircraft Pilots

The pilot is an important aircraft subsystem, and a complete analysis of aircraft flight characteristics requires attention to pilot operations. Depending on the type of aircraft, human pilots can have varying degrees of flight authority. The most common situation is that the pilot directly controls the aircraft flight conditions using manual flight control inputs, namely the throttle, the elevator deflection, the rudder deflection, and the differential deflection of the ailerons. In more advanced aircraft, the flight conditions are controlled by the pilot but with aid from an automatic control system, often referred to as an autopilot. In some of the most advanced aircraft, autonomous operation is possible where the flight conditions are completely controlled by the autopilots, with little or no supervision by a human.

Pilots operate aircraft according to flight operational protocols. These are an extensive set of flight rules that pilots must follow within the common airspace. The two main flight protocols are visual flight rules and instrument flight rules. Visual flight rules are most restrictive; they are required for low-speed general aviation aircraft with few flight instruments. Instrument flight rules apply to high-speed aircraft that are suitably equipped with flight instrumentation and flown by certified pilots.

In the subsequent development, it is sufficient to consider the pilot, or equivalently the autopilot, as providing control input commands that are used to keep the aircraft in a desired steady flight condition or to maneuver the aircraft from one steady flight condition to another. The four types of flight control inputs are the elevator, the ailerons, the rudder, and the throttle. All flight conditions and all flight maneuvers can be obtained by appropriate adjustment of these four flight control inputs. Subsequently, a complete analysis is developed that describes how a given steady flight condition is achieved by appropriate selection of the values of the flight control inputs. Flight maneuvers are also analyzed and expressed in terms of the required changes for these four flight control inputs.

1.10 Autonomous Aircraft

Some aircraft, such as small hobbyist radio-controlled aircraft or uninhabited aerial vehicles (UAVs), can be controlled through a remote operator. In this case, the remote operator is effectively the pilot in the sense that the operator flies the aircraft by adjusting the elevator, ailerons, rudder, and throttle.

It is possible, within limited environments, to develop aircraft that fly with complete or nearly complete autonomy. These autonomous flight vehicles require the development of advanced computer systems, often based on advanced control and artificial intelligence theories, that can make automatic flight decisions without direct intervention from a human. This is a flight technology that is growing rapidly; the fundamental flight principles described herein form the basis for many of these new developments.

1.11 Interconnection and Integration of Flight Systems

The flight subsystems of a single aircraft have been briefly described. The complete aircraft should be viewed as an interconnection of all of these flight subsystems. That is, aircraft flight operations depend on all of the flight subsystems working together. The concept of a system interconnection means that the outputs of one subsystem can be viewed as inputs to other subsystems. This flight interconnection perspective is very powerful, and it is essential to understand the flight operations of a single complex aircraft.

A topic of current study in the research and development community is the coordination of multiple aircraft, referred to as an aircraft team, to achieve some overall cooperative mission or flight formation. This requires a high level of integration of all of the aircraft that constitute the aircraft team. The flight properties of the aircraft team depend on the flight properties of the individual aircraft and the coordination strategy that is employed to control the team. This topic is not discussed further here, but it clearly requires, as background, a detailed knowledge of the flight properties of a single aircraft.