CHAPTER 1

Introduction

1.1 Overview

This book begins with a brief historical introduction, surveying our aeronautical legacy to motivate readers by describing the remarkable progress we have made from mythical conceptions of flight to high-performance aircraft with capabilities unimagined by early aeronautical pioneers. This chapter continues with offering a brief introduction to aircraft fundamentals and aircraft flight mechanics, which form the basics of aircraft performance. The chapter also presents the issues involved with units and dimensions in this context.

1.2 Brief Historical Background

Many books cover the broad sweep of aeronautical history, while others discuss specific accomplishments and famous people's achievements in aeronautics. References [1] to [4] are good places to start your exploration. Innumerable web sites on historical topics and technological achievements exist; simply enter keywords such as Airbus, Boeing, or anything that piques your curiosity, and you will find a wealth of information.

1.2.1 Flight in Mythology

People's desire to fly is ancient – every civilization has their early imaginations embedded in mythologies. In human efforts there are the well-known examples such as Daedalus/Icarus, vimanas (aircraft), flying carpets, flying chariots, and so on. In creatures, there are the bird-men (Garuda), flying horses (Pegasus/Sleipnir), flying dragons – our imagination of flight is universal.

History is unfortunately more "down to earth" than mythology, with stories about early pioneers who leapt from towers and cliffs, only to leave the Earth in a different but predictable manner because they did not respect natural laws. Our dreams and imagination became reality only a little over a century ago on 17 December 1903, when the Wright brothers succeeded with the first powered heavier-than-air flight. It only took 65 years from that date to land a man on the Moon.

1.2.2 Fifteenth to Nineteenth Centuries

Tethered kites are recorded to have flown in China as long ago as 600 BC. However, the first scientific attempts to design a mechanism for aerial navigation are credited to Leonardo da Vinci (1452–1519). He was the true "grandfather" of modern aviation, even if none of his

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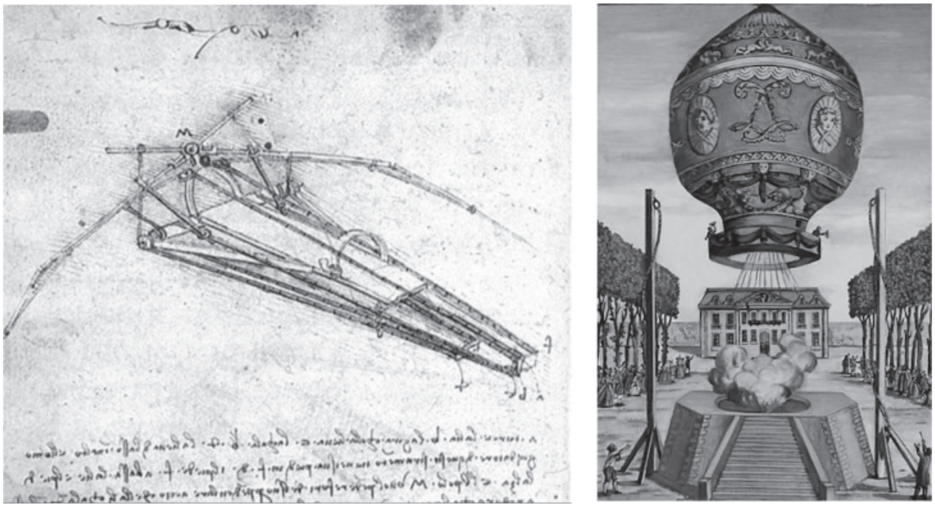
machines ever defied gravity (Figure 1.1), because he sketched many contraptions in his attempt to make a mechanical bird. Birds possess such refined design features that the initial human path into the skies could not take that route, but today's micro-air devices are increasingly exploring natural designs. After da Vinci, there was an apparent lull for more than a century until Sir Isaac Newton (1642–1727), who computed the power required to make sustained flight. Perhaps we lack the documentary evidence, but we are convinced that the human fascination with and endeavour for flight did not abate. Flight is essentially a practical matter, so real progress paralleled other industrial developments (e.g. isolating gas required for buoyancy).

While it appears that Bartolomeu de Gusmao may have demonstrated balloon flight in 1709 [4] in Portugal, information on this event is still lean. So we credit Jean-François Pilâtre de Rozier and François Laurent d'Arlandes as the first people to effectively defy gravity, using a Montgolfier balloon (Figure 1.1) in France in 1783. For the first time, it was possible to sustain and somewhat control flight above the ground at will. However, these balloon pioneers were subject to the prevailing winds and were thus limited in their navigational options. To become airborne was an important landmark in human history. The Montgolfier brothers (Joseph and Etienne) should be considered among the "fathers" of aviation. In 1784, Jean-Pierre Blanchard (France) with Dr John Jeffries (USA) added a hand-powered propeller to a balloon and made the first aerial crossing of the English Channel on 7 January 1785. (Jules Verne's fictional balloon trip around the world in 80 days became a reality when the late Steve Fossett circumnavigated the globe in fewer than 15 days in 2002.) In 1855, Joseph Pline was the first to use the word *aeroplane* in a paper he wrote proposing a gas-filled dirigible glider with a propeller.

It was not until 1804 that the first recorded controllable heavier-than-air machine to stay freely airborne was recorded when Englishman Sir George Cayley constructed and flew a kite-like glider (Figure 1.2) with movable control surfaces. In 1842, the English engineer Samuel Henson secured a patent on an aircraft design that was driven by a steam engine.

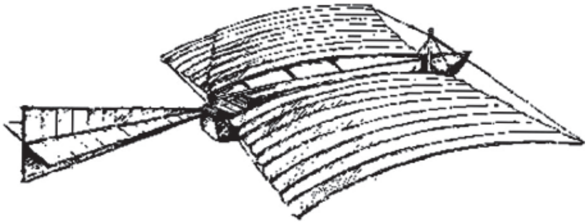
With his brother Gustav, Otto Lilienthal was successfully flying gliders (Figure 1.2) in Berlin more than a decade (1890) before the Wright Brothers' first experiments. His flights



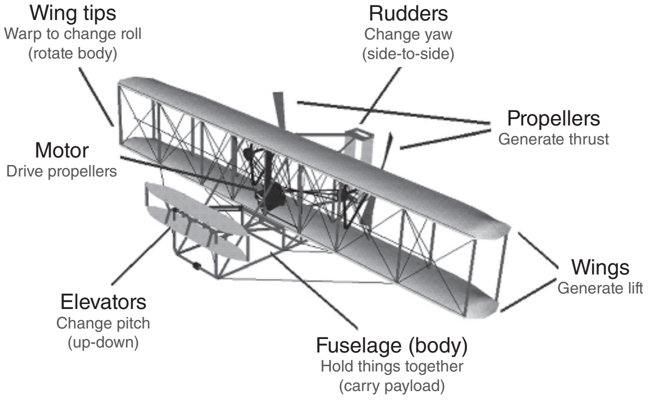
■ **FIGURE 1.1** **Early concepts and reality of flying: Leonardo da Vinci's flying machine, and the Montgolfier Balloon (reproduced with permission of NASA)** were controlled but not sustained. The early flight machine designs were hampered by an overestimation of the power requirement needed for sustained flight. This mistake (based in part on Newton's, among others, calculations) may have discouraged attempts of the best German engine-makers of the time to build aircraft engines because they would have been too heavy. Sadly, Lilienthal's aerial developments ended abruptly and his experience was lost when he died in a crash in 1896.

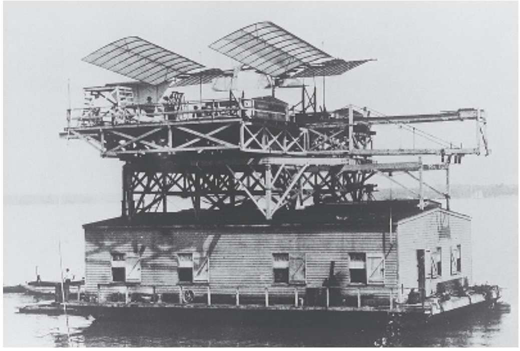
1.2.3 From 1900 to World War I (1914)

The question of who was first in flight is an important event to remember. The Wright Brothers (United States) are recognized as the first to achieve sustained, controlled flight in a heavier-than-air manned flying machine (Wright Flyer, Figure 1.3). Before discussing their achievement, some "also-rans" deserve mention. John Stringfellow accomplished the first powered flight of an unmanned heavier-than-air machine in 1848 in England. In France, Clement Ader also made a successful flight in his "Eole". Gustav Weisskopf (Whitehead), a Bavarian who migrated to the US, claimed to have made a sustained, powered flight [3] on 14 August 1901, in Bridgeport, Connecticut. Karl Jatho of Germany made a 200-foot hop (longer than the Wright Brothers first flight) powered (10-HP Buchet engine) flight on 18 August 1903. At what distance a "hop" becomes a "flight" could be debated. Perhaps most significant are the efforts of



■ FIGURE 1.2 Early heavier-than-air unpowered aircraft: Cayley's kite plane, and one of Lilienthal's gliders (reproduced with permission of NASA)





■ FIGURE 1.3 Early heavier-than-air powered aircraft: the Wright Flyer, and Langley's Aerodrome (reproduced with permission of NASA)

Samuel P. Langley, who made three attempts to get his designs (Aerodrome) airborne with a pilot at the controls (Figure 1.3). His designs were aerodynamically superior to the Wright flyer, but the strategy to ensure pilot safety resulted in structural failure while catapulting from a ramp toward water. His model aircraft were flying successfully in 1902. (To prove the capability, subsequently in 1914 Curtiss made a short flight with a modified Aerodrome.) The failure of his aircraft also broke Professor Langley; a short time afterwards, he died of a heart attack. Professor Langley, a highly qualified scientist, had substantial government funding, whereas the Wright brothers were mere bicycle mechanics without any external funding.

The Wright Brothers' aircraft was inherently unstable, but good bicycle mechanics that they were, they understood that stability could be sacrificed if sufficient control authority was maintained. They employed a foreplane (canard) for pitch control, which also served as a stall-prevention device. Modern designs have reprised this solution as seen in the Burt Rutan-designed aircraft. Exactly a century later, a flying replica model of the Wright Flyer failed to lift off on its first flight. A full-scale non-flying replica of the Wright Flyer is on display at the Smithsonian Museum in Washington, DC. This exhibit and other similar museums are well worth a trip. Strangely, the Wright Brothers did not exploit their invention; however, having been shown that sustained and controlled flight was possible, a new generation of aerial entrepreneurs quickly arose. Newer inventions followed in rapid succession, from pioneers such as Alberto Santos Dumas, Louis Bleriot, and Glenn Curtiss to name but a few. The list grew rapidly. Each inventor presented a new contraption, some of which demonstrated genuine design improvements. Fame, adventure, and "*Gefühl*" (feelings) were the drivers, since the early years saw little financial gain from selling "joy rides" and air shows – spectacles never seen before then and still appealing to the public today.

It did not take long to demonstrate the advantages of aircraft for mail delivery and military applications. At approximately 100 miles per hour (mph), on average, aircraft were travelling three times faster than any surface vehicle – and in straight lines. Mail was delivered in less than half the time. The potential for military applications was dramatic and well demonstrated during World War I. About a decade after the first flight in 1903, aircraft manufacturing had become a lucrative business. The Short Brothers and Harland (now part of the Bombardier Aerospace group) was a company that started aircraft manufacturing by contracting to fabricate the Wright designs. The company is now the oldest surviving aircraft manufacturer still in operation. In 2008, it celebrated its centenary, the first aircraft company to do so.

1.2.4 World War I (1914–1918)

Balloons were the earliest (second half of nineteenth century) airborne military vehicle, but controlled aircraft replaced their role as soon their effectiveness were demonstrated just before World War I. Their initial role was as an observation platform, and soon their military offensive capabilities (bombing, dogfights, etc.) were established. Their combat effectiveness became a decisive factor for military strategy. This rapidly attracted entrepreneurs in both private and public sectors. On both sides of the Atlantic the number of aircraft and engine designs and manufacturing establishments exceeded more than 100 organizations. With the growing recognition of the potential of military aircraft applications, the actual demand was in Europe. Serious military aircraft design activities began after war broke out. German aeronautical science and technologies made rapid advances.

This section shows how quickly the aircraft industry grew within a decade of the first flight, initially driven by military application. This is the period that lay the foundations of what was to come subsequently. The section is kept brief by giving only a few aircraft examples here.

***In the US*:** In 1908, the US Army accepted tender for military aircraft, and after extensive tests the Signal Corps accepted Wright Model A, powered by a 35 HP engine (Figure 1.4) in 1909. In 1912 the Wright Model B was used for the first time to demonstrate the firing of a machine gun from a airplane. Soon after, Glenn Curtiss became the dominant US aircraft designer. Curtiss aircraft introduced naval carrier-based flying during 1910–11. The company became early pioneers of producing military flying boats: planes that could take off and land in water. One of the earlier designs was the Curtiss F4 (Figure 1.4). The Boeing Company was started around this time. Among the famous names of early aviation are Martin, Packard,

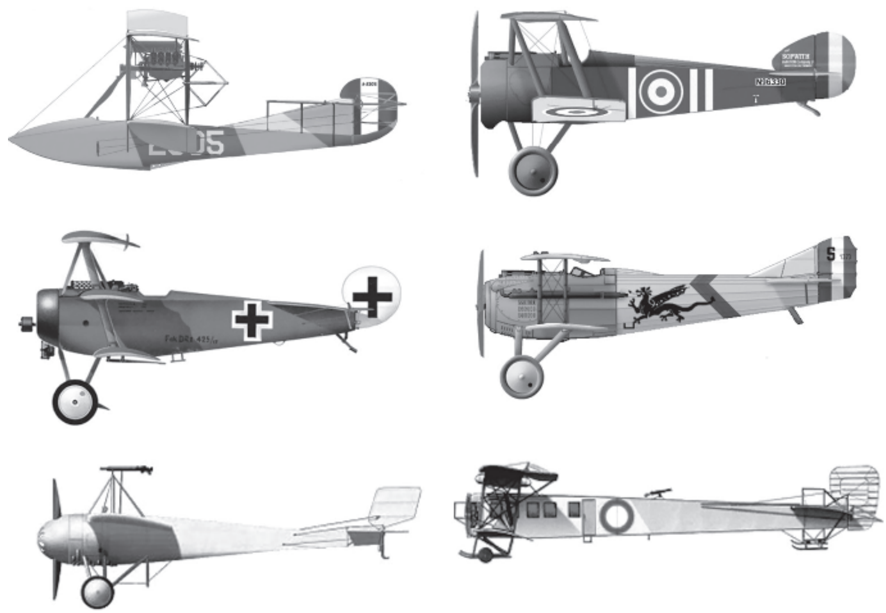


FIGURE 1.4 **Very early powered aircraft (World War I). Left panel: top, Curtiss F4 (US) (reproduced with permission of www.wp.scn.ru/); middle, Fokker Dr1 (Germany) (reproduced with permission of www.fokkerdr1.com/); bottom, Caproni Ca.20 (Italy) (reproduced with permission of www.airlinepicture.blogspot.com). Right panel: top, Sopwith Camel (UK) (reproduced with permission of www.worldac.de/); middle, SPAD S VII (France) (reproduced with permission of www.greatwarflyingmuseum.com); bottom, Sikorsky Ilya Muromets Bomber (reproduced with permission of www.aviastar.org/air/russia). See Table 1.1 for their performance summary**

TABLE 1.1
Performance summary of the aircraft in Figure 1.4

	Curtiss F4 flying boat	Sopwith Camel	Fokker Dr1	SPAD S VII	Caprioni Ca.20	Ilya Mouromets
Engine, HP	2×275	130	110	150	110	4×148
Wing area, ft^2	1216	231	201	192	144	1350
MTOM, lb	10,650	1455	1292	1632	≈1290	12,000
Max. speed, knots	85	115	185	119	100	110

Vaught, and so on; possibly in excess of two dozen aircraft and engine design and manufacturing companies emerged in the US during this period. Despite this, America introduced arguably superior European-designed military aircraft into their armed forces.

***In the UK*:** Upon the recommendation of the British Defence Ministry in 1911, the Royal Flying Corps (RFC) was formed in 1912. In 1918 it merged with the Royal Naval Air Service to form the Royal Air Force (RAF). The Royal Aircraft Factory B.E.2 was a single-engined two-seat biplane, in service with the RFC in 1912. They were used as fighters, interceptors, light bombers, trainers and reconnaissance aircraft. A more successful design with better capabilities was the single-seat Sopwith Pup. It entered service in the autumn of 1916. The Avro 504 (100–130 HP) and Sopwith Camel (1913, 110 HP – Figure 1.4) are some of the well-known aircraft of the time. Some of the other famous UK aircraft of the time bore the names of Armstrong-Whitworth, A.V. Roe, Blackburn, Bristol, Boulton/Paul, De Havilland, Fairey, Handley Page, Short Brothers, Supermarine, Vickers, and Westland.

***In Germany*:** *Die Fliegertruppen des Deutschen Kaiserreiches* (the Flier Troops of the German Kaiser Empire) of the Imperial German Army Air Service was formed in 1910, and changed its name to the Luftstretkräfte in 1916 (this became the Luftwaffe in the mid-1930s). Advances made by German aeronautical science and technologies produced many types of relatively high performance aircraft at the time. These saw action during World War I. The triplane Fokker Dr1 (Figure 1.4) was perhaps the most famous fighter of the period. The triplane was flown by the famous “Red Baron”, Rittmeister Manfred Freiherr von Richthofen, the top-scoring ace of World War 1 with 80 confirmed kills. Another successful German military airplane, the Albatross III, served on the Western Front until the end of 1917. The Junkers D.I was the first ever cantilever monoplane design to enter production. It utilized corrugated metal wings and front fuselage, with a fabric covering being used only on the rear fuselage. The Friedrichshafen FF.33 was one of the earliest German single-engine amphibious reconnaissance biplanes (1914). Some of the other famous German aircraft of the time bore the names of A.E.G., Aviatik, D.F.W., Fokker, Gotha (Gothaer Waggonfabrik), Halberstadt, Hannoversche, Junkers, Kondor, Roland, L.V.G., and Zeppelin.

***In France*:** The French Air Force (*Armée de l’Air*, ALA) is the air force of the French Armed Forces. It was formed in 1909 as the *Service Aéronautique*, as part of the French Army, and was made an independent military branch in 1933. The first Bleriot XIs entered military service in France in 1910. Other famous French military aircraft are Nieuport 10 (1914, 80 HP) and their subsequent designs. The SPAD S VII (Figure 1.4) was a successful French fighter aircraft of World War I used by many countries. The Caudron G.4 series was the first French-built twin-engine bomber biplane platform introduced in the early years of World War I. Some of the other famous French aircraft of the time bore the names of Hanriot, Maurice Farman, Moraine-Saulnier, and Salmson. Many countries, such as the UK, the US, Italy and Russia, bought French military aircraft for their Air Force.

***Other European Countries*:** Aircraft design and manufacturing activities in other European countries, such as Italy, Russia, the Scandinavian countries, Spain and Portugal, were also vigorously pursued. Only Italian and Russian designs are briefly given below.

Italy could claim to be amongst the earliest to experiment with military aviation. As early as 1884, before powered heavier-than-air vehicles, the *Regio Esercito* (Italian Royal Army) operated balloons as observation platforms. During the early World War I period, Caproni developed a series of successful heavy bombers. The Caproni Ca.20 (1914) was one of the first real fighter planes (Figure 1.4). It is a monoplane that integrated a movable, forward-firing drum-fed Lewis machine gun two feet above the pilot’s head, firing over the propeller arc. Some of the other famous Italian aircraft of the time bore the names of Società Italiana Aviazione and Ansaldo.

The Russian Empire under the Czar had the Imperial Russian Air Force possibly before 1910. Russian aeronautical sciences had advanced research of the time through famous names like Tsiolkovsky and Zhukovsky. The history of military aircraft in Imperial Russia is closely associated with the name of Igor Sikorsky. He emigrated to the US in 1919; aircraft bearing his name are still produced. In 1913–14 Sikorsky built the first four-engine biplane, the Russky Vityaz. His famous bomber aircraft, the Ilya Muromets, is shown in Figure 1.4. Other famous aircraft of Russian origin of the time had the names Anade, Antara, Anadwa, and Grigorvich.

1.2.5 The Inter-War Period: the Golden Age (1918–1939)

The urgent necessity for military activities during World War I advanced aeronautical science and technology to the point where it presented an attractive proposition for business growth. The aeronautical activities in the peace period were deployed to increase industrial and national growth. The enhanced understanding of aerodynamics, aircraft control laws, thermodynamics, metallurgy, structural and system analyses ensured that aircraft and engine size and performance grew in rapid strides. A wide variety of innovative new designs emerged to cover wide applications in both military and civil operations. Records for speed, altitude and payload capabilities were updated at frequent intervals. This period is seen as the Golden Age of aeronautics.

With enhanced aeronautical knowledge to increase aircraft capabilities, availability of experienced pilots and public awareness offered the ideal environment to make commercial aviation a reality. Surplus post-war experienced pilots were available who could easily adapt to newer designs. They kept them engaged with performing air-shows and offering joy rides. In this period, aircraft industries geared up in defence applications and in civil aviation, with financial gain as the clear driver. The free market economy of the West contributed much to aviation progress; its downside, possibly reflecting greed, was under-regulation. The proliferation showed signs of compromise with safety issues, and national regulatory agencies quickly stepped in, legislating for mandatory compliance with airworthiness requirements (US, 1926). Today, every nation has its own regulatory agency.

One of the earliest applications of commercial operation with passenger flying was done on the modified Sikorsky Ilya Muromets (Figure 1.4). It had an insulated cabin with heating and lighting, comfortable seats, lounge and toilet. Fokker was a Dutch aircraft manufacturer named after its founder, Anthony Fokker. The company operated under several different names, starting out in 1912 in Schwerin, Germany, moving to the Netherlands in 1919. In the 1920s, Fokker entered its glory years, becoming the world's largest aircraft manufacturer. Its greatest success was the F.VIIa/3 m trimotor passenger aircraft, which was used by 54 airline companies worldwide. It shared the European market with the Junkers all-metal aircraft, but dominated the American market until the arrival of the Ford Trimotor, which copied the aerodynamic features of the Fokker F.VII, and Junkers structural concepts. In May 1927, Charles Lindberg won the Ortega Prize for the first individual non-stop transatlantic flight.

Early aircraft design was centred on available engines, and the size of the aircraft depended on the use of multiple engines. The combination of engines, materials, and aerodynamic technology enabled aircraft speeds of approximately 200 mph; altitude was limited by human physiology. In the 1930s, Durener Metallwerke of Germany introduced *duralumin*, with higher strength-to-weight ratios of isotropic material properties, and dramatic increases in speed and altitude resulted.

1.2.6 World War II (1939–1945)

The introduction of duralumin brought a new dimension to manufacturing technology. Structure, aerodynamics, and engine development paved the way for substantial gains in speed, altitude, and manoeuvring capabilities. These improvements were seen predominantly in World War II designs such as the Supermarine Spitfire, the North American P-51, the Focke-Wolfe 190, and the Mitsubishi Jeero-Sen. Multi-engine aircraft also grew to sizes never before seen.

The invention of the jet engine (independently by Whittle in the UK and von Ohain in Germany) realised the potential for unheard-of leaps in speed and altitude, resulting in parallel improvements in aerodynamics, materials, structures, and systems engineering. Heinkel He 178 was the first jet-powered aircraft (27 August 1939), followed by the Gloster E.28 on 15 May 1941.

1.2.7 Post World War II

A better understanding of supersonic flow and a suitable rocket engine made it possible for Chuck Yeager to break the sound barrier in a Bell X1 in 1949 (the aircraft is on show at the Smithsonian Air and Space Museum in Washington, DC). Tens of thousands of the Douglas C-47 Dakota and Boeing B17 Flying Fortress were produced. Post-war, the De Havilland Comet was the first commercial jet aircraft in service; however, plagued by several tragic crashes, it failed to become the financial success it promised.

The 1960s and 1970s saw rapid progress, with many new commercial and military aircraft designs boasting ever-increasing speed, altitude and payload capabilities. Scientists made considerable gains in understanding the relevant branches of science: in aerodynamics [4], concerning high lift and transonic drag; in materials and metallurgy, improving the structural integrity; and in solid-state physics. Some of the outstanding designs of those decades emerged from the Lockheed Company, including the F104 Starfighter, the U2 high-altitude reconnaissance aircraft, and the SR71 Blackbird. These three aircraft, each holding a world record of some type, were designed in Lockheed's Skunk Works, under the supervision of Clarence (Kelly) Johnson. I recommend that readers study the design of the nearly half-century-old SR71, which still holds the speed-altitude record for aircraft powered by air-breathing engines.

During the late 1960s, the modular approach to gas-turbine technology gave aircraft designers the opportunity to match aircraft requirements (i.e. mission specifications and economic considerations) with "rubberized" engines (see Section 7.2). This was an important departure from the 1920s and 1930s, when aircraft sizing was based around multiples of fixed-size engines. Chapter 7 describes the benefits of modular engine design. This advancement resulted in the development of families of aircraft design. Plugging the fuselage and, if necessary, allowing wing growth accessed a wider market area at a lower development cost because considerable component commonality could be retained in a family: a significant cost-reduction design strategy. Capitalistic objectives render designers quite conservative, forcing them to devote considerably more time to analysis. Military designs emerge from more extensive analysis – for example, the strange-looking Lockheed F117 is configured using stealth features to minimize radar signatures. Now, more mature stealth designs look conventional (e.g. the Lockheed F22).

1.3 Current Aircraft Design Status

A major concern that emerged in the commercial aircraft industry from the market trend and forecast analysis of the early 1990s was the effect of inflation on aircraft manufacturing costs. Since then, all major manufacturers and the subcontracting industries have implemented cost-cutting measures. It became clear that a customer-driven design strategy is the best approach for survival in a fiercely competitive marketplace. The paradigm of "better, farther, and cheaper to market" replaced, in a way, the old mantra of "higher, faster, and farther" [5]. Manufacturing considerations came to the forefront of design, and new methodologies were developed, such as DFM/A and Six Sigma.

With rising airfares, air travellers have become cost-sensitive. In commercial aircraft operations, the direct operating cost (DOC) depends more on the acquisition cost (i.e. unit price) than on the fuel cost (year 2000 prices) consumed for the mission profile. Today, for the majority of mission profiles, fuel consumption constitutes between 15% and 30% of the DOC, whereas the aircraft unit price contributes between three and four times as much, depending on the payload range [6]. For this reason, manufacturing considerations that can lower the cost of aircraft production should receive as much attention as the aerodynamic saving of drag counts. The situation would change if the cost of fuel exceeds the current airfare sustainability limit (see Chapter 17), when drag-reduction efforts regain ground.

The conceptual phase of aircraft design is now conducted using a multidisciplinary approach (i.e. concurrent engineering), which must include manufacturing engineering and an appreciation for the cost implications of early decisions; the “buzzword” is *integrated product and process development* (*IPPD*). Section 1.8 briefly describes typical project phases as they are practised currently. Margins of error have shrunk to the so-called zero tolerance so that tasks are done correctly the first time; the Six Sigma approach is one management tool used to achieve this end. The importance of environmental issues has emerged, forcing regulatory authorities to impose limits on noise and engine emission levels. Recent terrorist activities are forcing the industry and operators to consider preventative design features.

1.3.1 Current Civil Aircraft Trends

Current commercial transport aircraft in the 100 to 300 passenger classes all have a single slender fuselage, backward-swept low-mounted wings, two under-slung wing-mounted engines, and a conventional *empennage* (i.e. a horizontal and a vertical tail); this conservative approach is revealed in the similarity of configuration. The similarity in larger aircraft is the two additional engines; there have been three-engine designs, but only on a few aircraft, because the configuration was rendered redundant by variant engine sizes that cover the in-between sizes and extended twin operations (ETOPS). The largest commercial jet transport aircraft, the Airbus 380 (Figure 1.5), made its first flight on 27 April 2005, and is currently in service. The Boeing 787 Dreamliner (Figure 1.5) is the replacement for its successful Boeing 767 and 777 series, aiming at competitive economic performance.

The last three decades witnessed a 5–6% average annual growth in air travel, exceeding 2×109 revenue passenger miles (RPM) per year. Publications by the International Civil Aviation Organization (ICAO), the National Business Aviation Association (NBAA), and other journals provide overviews of civil aviation economics and management. The potential market for commercial aircraft sales is of the order of billions of dollars per year. However, the demand for air travel is cyclical and – given that it takes about four years from the introduction of a new aircraft design to market – operators must be cautious in their approach to new acquisitions. They do not

■ **FIGURE 1.5 Current wide-body large commercial transport aircraft: the Airbus 380 (reproduced with permission of Airbus), and the Boeing 787 Dreamliner (reproduced with permission of Boeing)** want new aircraft to join their fleet during a downturn in the air-travel market. Needless to say, market analysis is important in planning new purchases.

Deregulation of airfares has made airlines compete more fiercely in their quest for survival. The growth of budget airlines compared with the decline of established airlines is another challenge for operators. Boeing introduced its 737 twin-jet aircraft (derived from the three-engine B727, the bestseller at the time), and after nearly four decades of production to this day, has become the bestseller in the history of the commercial aircraft market. Of course, in that time, considerable technological advancements have been incorporated, improving the B737's economic performance by about 50%.

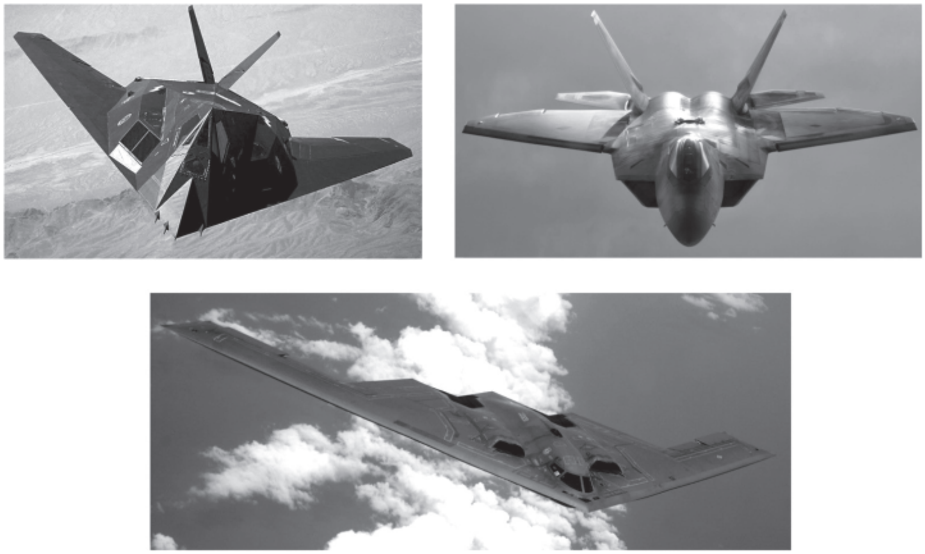
The gas-turbine turboprop offers better fuel economy than current turbofan engines. However, because of propeller limitations, the turboprop-powered aircraft's cruising speed is limited to about two-thirds of the high-speed subsonic turbofan-powered aircraft. For lower operational ranges (e.g., less than 1000 nautical miles (nm), the difference in sortie time would be of the order of less than half an hour, yet there is a saving in fuel costs of approximately 20%. If a long-range time delay can be tolerated (e.g. for cargo or military heavy-lift logistics), then large turboprop aircraft operating over longer ranges become meaningful. Advances in propeller technology are pushing turboprop powered aircraft cruising speeds close to the turbofan-powered aircraft high subsonic cruise speeds.

1.3.2 Current Military Aircraft Trends

Military aircraft designs have the national interest as a priority over commercial considerations. While commercial aircraft can earn self-sustaining revenue, military operations depend totally on taxpayers' money with no cash flow back, other than export sales that carry the risk of disclosure of tactical advantages. The cost frame of a new design has risen sufficiently to strain the economy of single nations. Not surprisingly, the number of new designs has drastically reduced, and military designs are moving towards multinational collaborations among allied nations, where the retention of confidentiality in defence matters is possible.

There are differences between civil and military design requirements (see Section 1.14.1). However, there are some similarities in their design processes up to the point when a new breakthrough is introduced – one thinks instinctively of how the jet engine changed in design in the 1940s. Consider the F117 Nighthawk (Figure 1.6); the incorporation of stealth technology appeared to be an aerodynamicist's nightmare, but it now conforms to something familiar in the shape of the F35 Lightning II (its prototype X35 is shown in Figure 1.6). We must not forget that military roles are more than just combat; they extend to transportation and surveillance (reconnaissance, intelligence gathering and electronic warfare). F35, Eurofighter, Rafale, Gripen, and Sukhoi 30 are the current frontline fighter aircraft. In strategic bombin, the B52 served for four decades and is to continue for another two decades – some design! The latest B2 bomber (Figure 1.6) looks like an advanced flying wing without the vertical tail.

Combat roles are classified as interdiction, air superiority, air defence and, when missions overlap, multi-role (see Section 10.4 for details). Action in hostile environments calls for special attention to: design for survivability; systems integration for target acquisition and weapons management; and design considerations for reliable navigation and communication. All told, it is a complex system, mostly operated by a single pilot – an inhuman task if the workload was not relieved by microprocessor-based decision-making. Fighter pilots are a special breed of aircraft operators with the best emotional and physical conditioning to cope with the stresses involved. Aircraft designers have a deep obligation to ensure combat pilot survivability. Unmanned aerial vehicle (UAV) technology is in the offing – the Middle-Eastern conflicts saw successful use of the Global Hawk for surveillance. Of late, UAVs are used as a weapon delivery system.



■ **FIGURE 1.6** **Current combat aircraft. Top left: F117 Nighthawk (reproduced with permission of the US Airforce/ Sgt Aaron Allmon; top right: X-35 (F35 experimental) (reproduced with permission of the US Airforce/Dana Russo); bottom, B2 Bomber (reproduced with permission of the US Airforce/Sgt Jeremy Wilson)**

1.4 Future Trends

It is clear that in the near future, vehicle capabilities will be pushed to the extent permitted by economic and defence factors and infrastructure requirements (e.g. navigation, ground handling, support, etc.). It is no exception from past trends that speed, altitude and payload will be expanded in both civilian and military capabilities. Coverage of the aircraft design process in the next few decades is given in [7]. In technology, smart materials (e.g. adaptive structure) will gain ground, microprocessor-based systems will advance to reduce weight and improve functionality, and manufacturing methodology will become digital. However, unless the price of fuel increases beyond affordability, investment in aerodynamic improvement will be next in priority.

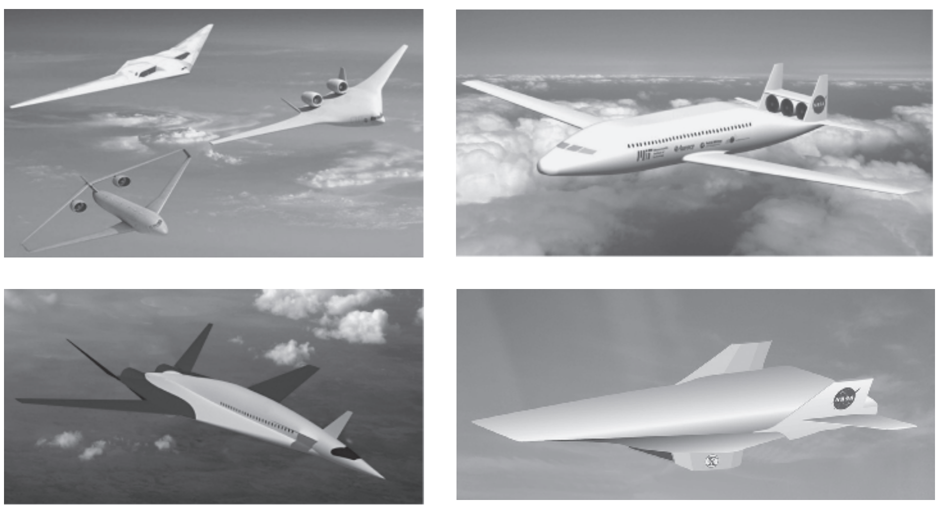
1.4.1 Trends in Civil Aircraft

Any extension of payload capability will remain subsonic for the foreseeable future, and will lie in the wake of gains made by higher-speed operational success. High-capacity operations will remain around the size of the Airbus 380. Some well-studied futuristic designs (Figure 1.7) have the possibility of further size increases. A blended-wing body (BWB) can use the benefits of the wing-root thickness being sufficiently large to permit merging (Figure 1.7, top) with the fuselage, thereby benefiting from the fuselage’s contribution to lift and additional cabin volume. Another alternative would be that of the joined-wing concept (Figure 1.7, bottom). Studies of twin-fuselage, large transport aircraft also indicate potential. A joined fuselage (Figure 1.7) is also a well studied concept.

The speed–altitude extension will progress initially through supersonic transports (SSTs) and then hypersonic transport (HST) vehicles. SST technology is well proven by three decades of the Anglo-French-designed Concorde, which operated above Mach 2 at altitudes of 50,000 feet carrying 128 passengers.

The next-generation SST will have about the same speed-altitude capability (possibly less in speed capability, around Mach 1.8), but the size will vary from as few as ten business passengers to approximately 300 passengers (Figure 1.7) to cover at least transatlantic and transcontinental operations. Transcontinental operations would demand sonic-shock strength reduction through aerodynamic gains rather than speed reduction; anything less than Mach 1.6 has less to offer in terms of time savings. The real challenge would be to have HST (Figure 1.7) operating at approximately Mach 6 that would require operational altitudes above 100,000 ft. Speeds above Mach 6 offer diminishing returns in time saved because the longest distance necessary is only about 12,000 nm (i.e. about 3 hours of flight time). Military applications for HST vehicles are likely to precede civilian applications, and small-scale HSTs have been flown recently.

The concept of rocket propulsion in modern application came from Von Braun's V2 rocket, an idea taken from Tippu's success in using rockets against the British-led Indian army at the Battle of Srirangapatna in 1792 [8]. The experience of Tippu Sultan's rockets led the British to develop missiles at the Royal Laboratory of Woolwich Arsenal, under the supervision of Sir William Congreve, in the late eighteenth century. A new type of speed-altitude capability will come from suborbital space flight (tourism) using rocket powered aircraft, as demonstrated by Rutan's Space Ship Two that hitchhikes with the White Knight to altitude (Figure 1.8), from where it makes the ascent. Interest in this aircraft has continued to grow; the prize of $10 million offered could be compared with that of a transatlantic prize followed by commercial success.



■ **FIGURE 1.7**
Current combat aircraft. Top left: blended wing aircraft; top right: joined twin fuselage; bottom left, supersonic transport aircraft; bottom right, hypersonic aircraft (all photos reproduced with permission of NASA)

■ **FIGURE 1.8**
White Knight carrying Space Ship Two

Both operators and manufacturers will be alarmed if the price of fuel continues to rise to a point where the air-transportation business finds it difficult to sustain operations. The industry would demand that power plants use alternative fuels such as biofuel, liquid hydrogen (LOH), and possibly nuclear power for large transport aircraft covering long ranges. Aircraft fuelled by LOH have been used in experimental flying for some time, and fossil fuel mixed with biofuel is currently being flight-tested.

A new type of vehicle known as a ground-effect vehicle is a strong candidate for carrying a large payload (e.g. can be bigger than Airbus 380 aircraft) and flying close to the surface, almost exclusively over water. (A ground-effect vehicle is not really new: the Russians built a similar vehicle called the *Ekranoplan*, but it did not appear in the free-market economy.)

Smaller Bizjets and regional jets will morph, and unfamiliar shapes may appear on the horizon, but small aircraft in personal ownership used for utility and pleasure flying are likely to revolutionize the concept of flying through their popularity, similar to how the automobile sector grew. The revolution will occur in short-field capabilities, with vertical takeoffs, and safety issues in both design and operation. Smaller aircraft used for business purposes will see more private ownership to stay independent of the more cumbersome airline operations. There is a good potential for airparks to grow. Various “roadable” aircraft (flying cars) have been designed. The major changes would be in system architecture through miniaturization, automation, and safety issues for all types of aircraft.

1.4.2 Trends in Military Aircraft

Progress in military aircraft would defy all imaginations. Size and shape would be as small as insects (micro-aircraft – dragonfly drones) for surveillance, to larger than any existing kind [9]. Vehicles as small as 15 cm and 1 kg mass have been successfully built for operation. Prototypes much smaller have been successfully flown.

As system-processing power grows, the capability to make weapon delivery decisions advances to an accuracy that could eliminate an onboard human interface, and thereby at one stroke the question of pilot survivability is taken out of the design process, which in turn permits the aircraft to operate at higher load, improving combat capability. Reliance on in-built intelligence would certainly make more remotely piloted vehicles (RPVs) come into in operation. Other terminologies are *unmanned*, *unoccupied*, and *pilotless*. However, unmanned aerial vehicle (UAV) is the prevalent terminology. Nations who can afford it have already entered the race to develop UAVs. Figure 1.9 shows an operational UAV, Ikhana, used for imaging. Futuristic concepts are the Boeing X45A and US Navy X47B (Northrop), as JUCAS (Joint Unmanned Combat Air System).

Once again it is the electronics that would play the main role, although aerodynamic challenges on stealth, manoeuvre and improved capability/efficiency would be as important as structural/material considerations. Engine development would also be a parallel development with all of these discoveries/inventions.

FIGURE 1.9 **Ikhana (General Atomics) (reproduced with permission of General Atomics Aeronautical Systems, Inc.)**

1.4.3 Forces and Drivers

This section discusses the current status of forces and drivers that control design activities. The current aircraft design strategy is linked to industrial growth, which in turn depends on national infrastructure, governmental policies, workforce capabilities, and natural resources; these are generally related to global economic-political circumstances. More than any other industry, the aerospace sector is linked to global trends. A survey of any newspaper provides examples of how civil aviation is affected by recession, fuel price increases, spread of infectious diseases and international terrorism. In addition to its importance for national security, the military aircraft sector is a key element in several of the world's largest economies. Indeed, aerospace activities must consider the national infrastructure as an entire system. A skilled labour force is an insufficient condition for success if there is no harmonization of activity with national policies; the elements of the system must progress in tandem. Because large companies affect regional health, they must share socioeconomic responsibility for the region in which they are located.

The current status stems from the 1980s when returns on investment in classical aeronautical technologies such as aerodynamics, propulsion, and structures began to diminish. Around this time, however, advances in microprocessors enabled the miniaturization of control systems and the development of microprocessor-based automatic controls, which gave additional weight-saving benefits. Dramatic but less ostensible changes in aircraft management began to be embedded in design. At the same time, global political issues raised new concerns as economic inflation drove man-hour rates to a point at which cost-cutting measures became paramount. In the last three decades of the twentieth century, man-hour rates in the West rose four to six times (depending on the country), resulting in aircraft price hikes (typically by about six times for the Boeing 737 – of course, accompanied by improvements in design and operational capabilities.) Lack of economic viability resulted in the collapse or merger/takeover of many well-known aircraft manufacturers. The number of aircraft companies in Europe and North America shrank by nearly three-quarters; currently, only two aircraft companies (Boeing and Airbus) in the West are producing large commercial-transport aircraft. Bombardier Aerospace and Embraer of Brazil have recently entered the large-aircraft market, joining the Russians, the Chinese and the Japanese. Over time, aircraft operating cost terminologies have evolved, and currently, the following standardized definitions are used in this book:

IOC (indirect operating cost):	Comprises costs not directly involved with the sortie (trip).
COC (cash operating cost):	Comprises the trip (sortie) cost elements.
FOC (fixed operating cost):	Comprises cost elements even when not flying but related to trip cost.
DOC (direct operating cost):	= COC + FOC.
TOC (total operating cost):	= IOC + DOC.

1.5 Airworthiness Requirements

From the days of barnstorming and stunt flying in the 1910s, it became obvious that commercial interest had the potential to short-circuit safety considerations. Government agencies quickly stepped in to safeguard people's security and safety without deliberately harming commercial interest. Western countries developed and published thorough systematic rules – these are in the public domain (see relevant websites). In civil applications, they are the Federal Aviation

Regulations or FAR and Certification Standards published by the European Aviation Safety Agency, EASA (formerly Joint Aviation Requirements (JARs) defined by the Joint Aviation Authorities, JAA); both are quite close. The author prefers to work with the established FAR at this point. In military applications, the standards are Milspecs (US) and Defense Standard 970 (earlier AvP 970 – UK); they do differ in places.

The US Government have 50 titles of Code of Federal Regulations (CFRs) published in the Federal Register, covering wide areas subject to federal regulations. The Federal Aviation Regulations (or FARs), are rules prescribed by the Federal Aviation Administration (FAA) governing all aviation activities in the US under title 14 of the CFRs, which covers wide varieties of aircraft-related activities in many parts, of which this book deals mainly with Parts 23, 25, 33 and 35. However, another set of regulations in Title 48 of CFRs is the Federal Acquisitions Regulations, and this has led to confusion with the use of the acronym "FAR". Therefore, the FAA began to refer to aerospace-specific regulations by the term "14 CFR part XX" instead of FAR. There is a growing tendency in the industry to adapt to using 14 CFR part XX. However, to retain the use of FAR meaning Federal Aviation Regulation is still acceptable, and in this book the authors continue with the use of the older practice of the term FAR.

Safety standards were developed through multilateral discussions between manufacturers, operators and government agencies, which continue even today. These minimum standards come as regulations and are mandatory. The regulatory aspects have two kinds of standards, as follows.

- **Airworthiness Standards**: These concern aircraft design by the manufacturers complying with regulatory requirements to ensure design integrity for the limiting performance. These are outlined in FAR 25/JAR 25 in extensive detail in a formal manner, and are revised when required. After substantiating the requirements through extensive testing, an Aircraft Flight Manual (AFM) is issued by the manufacturers for each type of aircraft designed.
- **Operating Standards**: These concern the technical operating rules to be adhered to by the operators, are outlined in FAR 121/JAR-OPS-1 in extensive detail in a formal manner, and are revised when required. The aircraft operational capabilities are substantiated by the manufacturer through extensive flight tests and are certified by the government certification agencies (e.g. FAA/JAA). The contents of the AFM are recast in a Flight Crew Operating Manual (FCOM) that outlines the aircraft limitations and procedures, along with the full envelope of aircraft performance data. Today, with the integration of computers in aircraft operation, it is possible to monitor aircraft performance (APM) for optimum operations. Today, the operational aspects require full understanding of operating microprocessor-based aircraft design.

In civil aviation, every country requires safety standards to integrate with their national infrastructure and climatic conditions for aircraft operation, as well as to relate to their indigenous aircraft designs. Therefore, each country started with their own design and operations regulations. As aircraft started to cross international borders, the standards for foreign-designed aircraft had to be re-examined and possibly re-certified to allow safe operation within their country. To harmonize the diverse nature of the various demands, the International Civil Aviation Organization (ICAO) was formed in 1948, to recommend the international minimum recommended standards. It has now become legal for international practice. However, within each country their own operational regulations might still apply; while countries in North America and some European countries adopt FAR 121, some other European countries follow JAR-OPS-1.

Aircraft operation is prone to litigation, as mishaps do occur. To avoid ambiguity as well to ensure clarity to design, FAA documentations are written in a very elaborate and articulated manner, demanding in-depth study in order to understand and apply them. It is for this reason this book does not exactly copy the FAR lines, but instead quotes the relevant Part number, outlining the requirements with explanations and supported by worked examples. The authors recommend that readers access the latest FAA publication; their web site at http://www.faa.gov/regulations_policies/faa_regulations/should prove useful. Most academic/aeronautical institute libraries necessarily keep FAR documents. For those in industry, these documents will be available there. Aeronautical engineering does not progress without these documents to guarantee a minimum safety in design and operation.

The FAR (14CFT) Part 25 has the most stringent airworthy compliance requirements. The FAR 23 (general aviation aircraft) and the FAR Part 103 (ultra-light aircraft) have considerably lower levels of requirements and use the same performance equations for analyses. This book deals only with the FAR (14CFR) Part 25.

1.6 Current Aircraft Performance Analyses Levels

Aircraft performance analysis is needed at the very early stages of the conceptual design phase and continues in every phase of the programme, updating capabilities as more accurate data are available until it is substantiated through flight tests. At the conceptual stage the performance prediction has to be sufficiently accurate to obtain management "go-ahead" for a programme that bears promise of eventual success. In the next phase the performance figures are fine-tuned to give a guarantee to potential operators. Industry must be able to perform aircraft performance analysis to a high degree of accuracy.

The analyses of aircraft performance cascade down from the preliminary study to final refinement by design engineers, followed by flight test substantiation, and eventually the engineers preparing the aircraft flight manuals (AFM) and the flight crew operating manual (FCOM) for operational usage. The various levels where aircraft performances are evaluated are briefly given below.

By the designers

(i) *At research level (feasibility study)*: In this stage, engineers examine new technologies and their capabilities to advance new aircraft designs, and examine possible modifications to improve existing designs. At this level, researchers explore newer aircraft performance capabilities, and optimize operational procedures using close-form equations that yield quick results for comparison and selection.

(ii) *Conceptual design level (Phase I of a project)*: This is the outcome of the feasibility study showing potential to progress the design towards market launch. In this phase, the study needs to be done in a specific manner to fix configurations in a family framework by sizing the aircraft with matched engines. In this phase, full aircraft analysis is not required. It only covers what is required to speak with potential customers with promising performance specifications sufficient to make comparisons with the competition. If successful, go-ahead for the programme is given at the end of the study.

(iii) *Detailed design level (Phases II and III)*: This is the post go-ahead phase analysis to give guarantees to potential customers. By now, more aerodynamic information is available through wind tunnel testing and CFD analyses. More detailed and accurate aircraft performance estimations are now possible.

(iv) *Final level (Phase IV)*: This is the final design phase, and aircraft performance tests are carried out to obtain certification of airworthiness. All technical/engineering and ground/flight-tested substantiation data are then passed to a dedicated group to prepare the aircraft flight manual (AFM) and the flight crew operating manual

(FCOM) for operational usage. The format of presenting aircraft performance in the AFM and the FCOM is different from the format of aircraft performance documents used by the designers; the former are derived from the latter. The performance documents prepared during Phases I, II and III, and used by engineers, contain predictive data that are substantiated through ground/flight tests. The full set of engineering data is given to experienced performance engineers at the dedicated customer support group who prepare the AFM and FCOM manuals for the airline operators. Typically, the design office uses the prevailing terminologies, but the AFM and the FCOM must incorporate standard formal terminologies specified by the airworthiness agencies to avoid any ambiguity. While preparing the operational manuals does not involve extensive computation, it requires articulated presentation since errors or lack of clarity are not acceptable. This book follows the typical terminologies used by engineers, along with introducing the synonymous formal terminologies to keep the readers informed.

By the operators

Using the manufacturer-supplied AFMs and FCOMs, the operators have their own performance engineers conduct analyses; the extent depends on the operators' strategic plans. Typically, these analyses are not as extensive as what the designers do, as it is not required. They cover: (i) market comparison to make selection of aircraft type; (ii) city-pair route planning (new or old routes); (iii) performance revisions on account of repairs; (iv) design modifications to improvement performance; and (v) accident/incidence analyses. Operating cost analyses form one of the core aspects of the study.

1.7 Market Survey

In a free market economy, industry cannot survive unless it grows; governmental subsistence can only be seen as a temporary relief. The starting point to initiate a new aircraft design project is to establish the key drivers – the requirements and objectives based on market, technical, certification and organizational requirements. These drivers are systematically analysed and then documented by the aircraft manufacturers (Table 1.2). Documents, in several volumes, describing details of the next layer of design specifications (requirements), are issued to those organizations involved with the project. Market surveys determine customer requirements, and user feedback guides the product. In parallel, the manufacturers incorporate the latest, but proven, technologies to improve design and stay ahead of the competition, always constrained

TABLE 1.2
The drivers leading to the final design

Market drivers from operators	Regulatory drivers from government	Technology drivers from industry
Payload-range, speed	Airworthiness regulations	Aerodynamics
Field performance	Policies (e.g. fare deregulation)	Propulsion
Comfort level	Route permission	Structures
Functionality	Airport fees	Materials
Maintenance	Interest rates	Avionics/electrical
Support	Environmental issues	Systems, fly-by-wire
Aircraft family	Safety issues	Manufacturing philosophy

by the financial viability of what the market can afford. Dialogue between manufacturers and operators continues all the time to bring out the best in the design.

Military product development has a similar approach, but would require some modifications to Table 1.2. Here, government is both the single customer and the regulatory body. Therefore, competition is only between the bidding manufacturers. The market is replaced by the operational requirements arising from perceived threats from potential adversaries. Column 1 of Table 1.2 then becomes "Operational Drivers", which includes weapons management and counter intelligence. Hence, this section on market survey is divided into civil and military customers as shown in Table 1.3. "Customer" is a broad-based term and is defined in this book in the manner given in Table 1.3.

In the UK military, the Ministry of Defence (MoD), as the single customer, searches for a product and floats a Request for Proposal (RFP) to the national infrastructure, where most manufacturers are run privately. It is nearly the same in the US under different terminologies. Product search is a complex process – the MoD must know the potential adversary's existing and future capabilities, and administrate national RD&D infrastructures to be ready with discoveries/innovations to supersede the adversary's capabilities. The Air Staff Target (AST) is an elaborate aircraft specification as customer requirement. A military project is of national interest and in today's practice the capable companies are invited first to produce a 'Technology Demonstrator' as proof of concept. The loser in the competition gets paid by the government for the demonstrator and learns a lot about very advanced technology for the next RFP or civilian design (so that, in a true sense, there is no loser) and the nation hones its technical manpower.

Although used, the authors do not think that RFP is an appropriate terminology in civil applications – here, who is making the request? It is important for the aircraft manufacturers to know the requirements of many operators and supply a product that meets the market's demands in performance, cost and time frames. Airline, cargo and private operators are the direct customers of the aircraft manufacturers, who do not have direct contact with the next level of customers (i.e. passengers and cargo handlers). Airlines do their market surveys of passenger and freight requirements and pass the information to the manufacturer. These are often established by extensive studies of target city pairs, current market coverage and growth trends, and passenger input. Their feedback comes with diverse requirements that need to be coalesced to a marketable product. A large order from a single operator could start a project, but manufacturers must cater for many operators to enlarge and stabilize their market share. The civil market is searched through a multitude of queries to various operators (airlines), nationally and internationally. In civil aviation, the development of national infrastructure must be run in coordination with the aircraft manufacturers and operators to ensure national growth. Airlines generate revenue by carrying passengers and freight; these provide the cash flow that supports the maintenance and development of the civil aviation infrastructure. Cargo generates important revenues for airlines and airports, and its market should not be underestimated, even if it means modifying older airplanes. Manufacturers and operators remain constantly in touch with each other in order to develop product lines with new and/or modified aircraft. The aircraft manufacturers need to

■ **TABLE 1.3**
Customers of aircraft manufacturers

	Civil customers	Military customers
Top level	Airline/cargo/private operators	MoD (single)
Next level	Passengers and cargo handlers	Foreign MoD
Revenue	Cash flows back through revenue earned	No operational revenue, possible export revenue

harmonize diversity in requirements in order to arrive at a point where the management decides to undertake a conceptual study to obtain “go ahead”. This is nothing close to the route taken by the MoD to initiate a RFP with a single customer demand.

The private or executive aircraft market is driven by operators who are closely connected to business interests and cover a wide spectrum of types, varying from four passengers to specially modified mid-sized jets.

Military aircraft utilization in peacetime is approximately 7500 hours, about a tenth that of commercial transport aircraft (≈75,000 hours), in its life-span. Peacetime military aircraft yearly utilization is very low (around 600 hours) compared with civil aircraft yearly utilization, which can exceed 3000 hours.

1.8 Typical Design Process

The typical aircraft design process follows the classical pattern of a systems approach. The official definition of a system adopted by the International Council of Systems Engineering (INCOSE – [10]) is that “a ‘system’ is an interacting combination of elements, viewed in relation to function”. The design “system” has an input (a specification/requirement), which undergoes a process (phases of design) to obtain an output (certified design through substantiated aircraft performance), as shown in Figure 1.10.

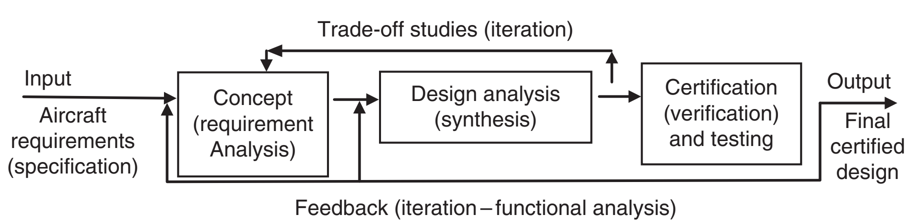
1.8.1 Four Phases of Aircraft Design

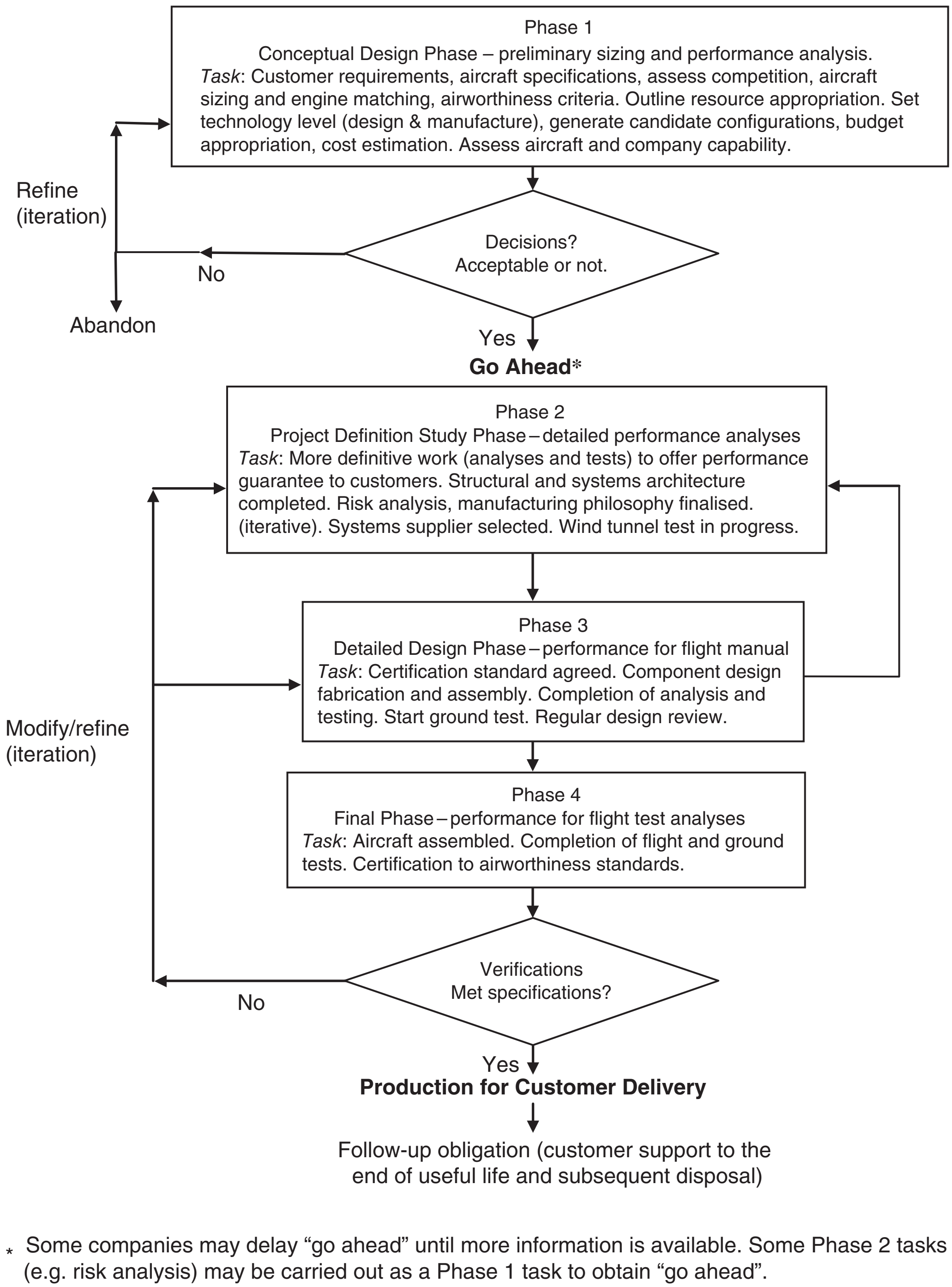
Aircraft manufacturing organizations conduct round-the-year exploratory work on research, design and technology development, as well as market analysis to search for a product, and when it is found, the project gets formally initiated in the four phases as shown in Figure 1.11, which is valid for both civil and military projects.

From organization to organization, the terminologies of the phases vary. The difference between the terminologies is trivial, as the task breakdown covered in various phases is about the same. For example, some may see Market Study and Specification Requirements as Phase 1, making Conceptual Study as Phase 2; some may define the Project Definition Phase (Phase 2) and Detailed Design Phase (Phase 3) as the Preliminary Design Phase and Full Scale Development Phase, respectively. Some would prefer to invest early on risk analysis in Phase 1, but it could be done at Phase 2 when the design is better defined, saving Phase 1 budgetary provision in case the project fails to get a “go-ahead”. Military programmes may require early risk analysis as they would be incorporating technologies yet to be proven in operation. Some may see disposal of aircraft at the end as part of the design phase of a project. Figure 1.11 offers a typical/generic pattern prevailing in industry.

Aircraft performance analyses are carried out in all four phases at various levels, as given below. The formulation of physics is the same for all; the difference lies in the extent of coverage and rigour for the performance evaluation required.

■ **FIGURE 1.10**
The aircraft design process





■ **FIGURE 1.11** **Introduction to the four phases of aircraft design and development**

Phase 1 ***Conceptual Design Phase***: In this phase, preliminary performance studies are conducted to size aircraft for a family of variants and find matched engines to meet market specifications: takeoff and landing, speeds at initial climb and cruise, and meeting the payload-range. These evaluations are primarily used by management to arrive at the "go-ahead" decision and also by potential customers. Expected accuracy of the results should be within less than ±5%.

Phase 2 ***Project Definition Study Phase***: After "go-ahead" is obtained, more definitive work (analyses and tests) are carried out in this phase to offer aircraft performance guarantees to customers. This also offers an opportunity to refine sizing and engine matching before metal cutting starts. Expected accuracy should be within less than ±3%.

Phase 3 ***Detailed Design Phase***: This is the time when accurate aircraft performances for the flight manual are carried out to some agreed certification standards. The equations of performance analyses are the same, but evaluated in detail for the full flight envelope for the allowable climatic conditions. Expected accuracy should be within less than ±2%.

Phase 4 ***Final Phase***: Aircraft performance for flight test analyses to calibrate with estimation. This is to ensure that aircraft performance does not fall short of the guaranteed values.

The methodologies presented in this book should cater for aircraft performance analyses for all the four stages. Details of activities of the various phases are described in the next sections.

Table 1.4 suggests a generalized functional envelope of aircraft design architecture, which is in line with the index given for commercial transport aircraft by the Aircraft Transport Association (ATA) [11], which recently changed name to A4A, Airlines for America. Further breakdowns of subsystems are given in the respective chapters.

The components of the aircraft as subsystems exist interdependently in a multidisciplinary environment, even if they have the ability to function on their own. For example, wing flap deployment on the ground is inert, while in flight it affects the vehicle motion. Individual components, such as the wing, nacelle, undercarriage, fuel system, air-conditioning, and so on, can also be seen as subsystems. Components are supplied for structural and system testing in conformance with airworthiness requirements in practice. Close contact is maintained with

■ TABLE 1.4
Aircraft systems

Design	Operation
Aerodynamics	Training
Structure	Product support
Power Plant	Facilities
Electrical/avionics	Ground/office
Hydraulic/pneumatic	Flight operations
Environmental control	
Cockpit/interior design	
Auxiliary systems	
Production engineering feedback	
Testing and certification	

planning engineers to ensure that production costs are minimized and to ensure that build tolerances are consistent with design requirements.

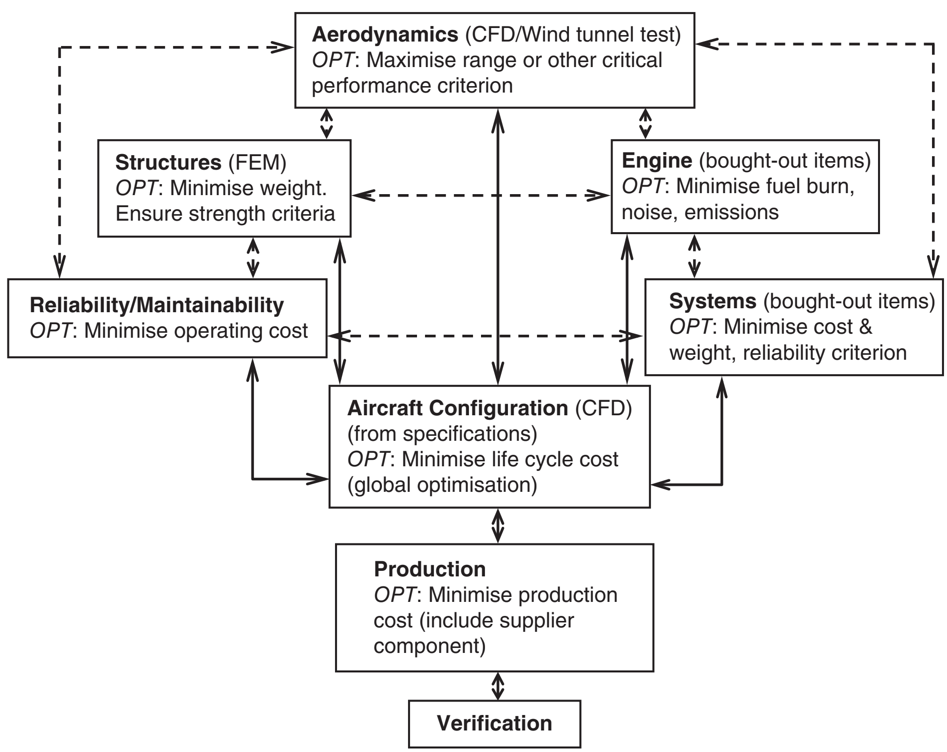
Extensive wind tunnel, structure and systems testing will be required early in the design cycle to ensure safe flight tests, leading to airworthiness certification approval. The multidisciplinary "systems" approach to aircraft design is carried out within the context of IPPD. The generic methodology has four phases (see next section) to get a new aircraft conceived, designed, built and certified. Civil projects usually proceed to pre-production build aircraft, which will be flight-tested and sold subsequently.

Military projects proceed with technology demonstrators as prototypes before "go-ahead" is given. Military technology demonstrators are normally scaled-down aircraft meant to substantiate untried cutting-edge technology. These are not sold for operational usages.

Company management sets up a "design built team" (DBT) to meet at regular intervals to conduct design reviews and make decisions on the best compromises through multidisciplinary analysis (MDA) and multidisciplinary optimization (MDO) as shown in Figure 1.12 – this is what is meant by IPPD (concurrent engineering) environment.

Specialist areas may optimize their design goals, but in the IPPD environment, compromise has to be sought. *Optimization of individual goals through separate design considerations may prove counterproductive and usually prevent the overall (global) optimization of ownership cost.* MDO offers good potential, but to obtain global optimization is not easy; it is still evolving. In a way, a global MDO, involving large numbers of variables, is still an academic pursuit. Industries are in a position to use sophisticated algorithms in some proven areas. One such situation is to reduce manufacturing cost by reshaping component geometry as a compromise to lower cost (i.e. to minimize complex component curvature). To offer a family of

■ **FIGURE 1.12**
Multidisciplinary analysis (MDA) and optimization (MDO) flowchart (IPPD)



variant aircraft the compromises are evident, as none of the individuals in the family are optimized, but together they offer the best value for money.

Once the aircraft has been delivered to the operators (customers), a manufacturer is not free from obligations. Manufacturers continue with support work on maintenance, design improvements and attention to operational queries, right up to the end of aircraft life. Modern designs are expected to achieve three to four decades of operation. Manufacturers may even face litigation if customers find cause to sue. Compensation payments have crippled some famous general aviation names. Fortunately, the 1990s saw a relaxation of the litigation laws in general aviation – after a certain period of time when a design is established, the manufacturer's liabilities are reduced – which resulted in a revitalization of the general aviation market. Military programmes involve support from "cradle to grave", that is, from delivery of the new aircraft to end of service life.

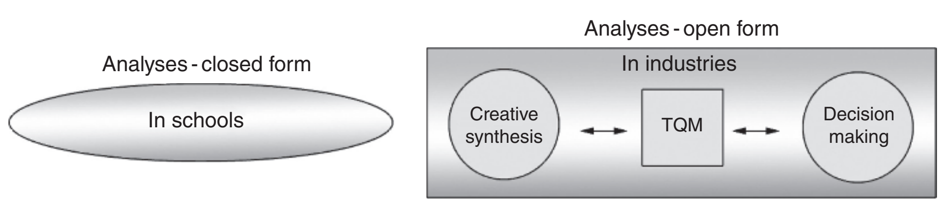
It is important to emphasize that the product must be "right-first-time". Mid-course changes add needless cost that could hurt the project – a big change may not even prove sustainable. Procedural methodologies such as the Six-Sigma approach have been devised to make sure changes are minimized.

1.9 Classroom Learning Process

To meet our objectives to offer close-to-industrial practice in this book, it would be appropriate here to harmonize some of the recognized gaps between academia and industry as discussed in [12] to [19]. Before we embark on dealing with the aircraft performance analyses, we will lay out our intended classroom learning process, as previously tested in industry and in academia.

It is clear that unless the engineer has sufficient analytical ability, it will be impossible for him/her to convert creative ideas into profitable product. Today's innovators who have no analytical and practical skills must depend on engineers to accomplish routine tasks under professional investigation, and to make necessary decisions to develop an idea into a marketable product.

Traditionally, universities develop analytical abilities by offering the fundamentals of engineering science. Courses are structured with all the material available in textbooks or notes; problem assignments are straightforward with unique answers. This may be termed a "closed-form" education. Closed-form problems are easy to grade and a teacher's knowledge is not challenged (relatively). Conversely, industry requires the tackling of "open-form" problems for which there is no single answer. The best solution is the result of interdisciplinary interaction of concurrent engineering within design built teams (DBTs), in which total quality management (TQM) is needed to introduce "customer-driven" products at the best value. Offering open-ended courses in design education that cover industrial requirements is more difficult and will challenge a teacher, especially when industrial experience is lacking. The associative features of closed- and open-form education are shown in Figure 1.13 [19].



■ **FIGURE 1.13 Associative features of "closed" and "open" form education (adapted from [19], American Institute of Aeronautics and Astronautics, Inc.)**

To meet industry's needs, newly graduated engineers need a brief transition time before they can become productive, in line with the specialized tasks assigned to them. They must have a good grasp of the mathematics and engineering sciences necessary for analysis and sufficient experience for decision-making. They must be capable of working under minimal supervision, with the creative synthesis that comes from experience that academia cannot offer. The industrial environment will require new recruits to work in a team, with an appreciation of time, cost, and quality under TQM, which is quite different from classroom experience. Today's conceptual aircraft designers must master many trades and specialize in at least one, not ignoring the state-of-the-art "rules of thumb" gained from past experiences; there is no substitute. They need to be good "number-crunchers" with excellent analytical ability. They also need assistance from an equally good support team to encompass wider areas. This is the purpose of the coursework in this book: to provide close-to-industry standard computations and engineering approaches necessary for analysis, and enough experience to work in a team.

For this reason, the authors emphasize that introductory class-work projects should be familiar to students so that they can relate to the examples and subsequently substantiate their work with an existing type. Working on an unfamiliar or non-existent design does not enhance the learning process at the introductory level. In industry, aircraft performance analyses are fully computerized for every phase of project work. However, in the classroom it is recommended to perform manual computation using spreadsheets.

Today, use of computer-aided design (CAD) is an integral part of engineering analyses. As an example, Figure 1.14 gives a 3D CAD drawing of an F16 fighter aircraft. 3D modelling provides fuller, more accurate shapes that are easy to modify, and facilitates maintenance of sequential configuration evolution. Accurate geometric details from CAD can be easily retrieved for drag estimation by the indispensable manual method.

There are considerably more benefits from CAD (3D) solid modelling; it can be uploaded directly into computational fluid dynamics (CFD) analysis to continue with aerodynamic estimations, as one of the first tasks is to estimate loading for structural analysis using the finite element method (FEM). The solid model offers accurate surface constraints for generating internal structural parts. CAD drawings can be uploaded directly to computer-aided manufacture (CAM) operations, ultimately leading to paperless design and manufacture offices. Vastly increased computer power has reached the desktop with parallel processing. Computer-aided engineering (CAE: e.g. CAD, CAM, CFD, FEM and systems analyses) is the accepted practice in the industry. Those who can afford supercomputers will

■ FIGURE 1.14
Typical 3D CAD drawing of F16 (reproduced with permission of Pablo Quispe Avellaneda, Naval Engineer, Peru)

have the capability to conduct research in areas hitherto unexplored or facing limitations (e.g. high-end CFD, FEM and multidisciplinary optimization (MDO)).

Finally, the authors recommend that performance engineers have some flying experience, which is most helpful in understanding the flying qualities of aircraft they are trying to analyze. Obtaining a licence requires effort and financial resources, but a few hours of planned flight experience would be instructive. One may discuss with the flight instructor what needs to be demonstrated, for example, aircraft characteristics in response to control input, stalling, "*g*" force in steep manoeuvres, stick forces, and so forth. Some universities offer a few hours of flight-tests as an integral part of aeronautical engineering courses; however, the authors suggest even more: hands-on experience under the supervision of a flight instructor. A driver with a good knowledge of the design features has more appreciation for the automobile.

1.10 Cost Implications

The authors emphasize here that there is a significant difference between civil and military programmes in predicting costs related to aircraft unit-price costing. The civil aircraft design has an international market with cash flowing back from revenues earned from fare-paying customers (i.e. passengers and freight) - a regenerative process that returns funds for growth and sustainability to enhance the national economy. Conversely, military aircraft design originates from a single customer demand for national defence and cannot depend on export potential – it does not have cash flowing back, and it strains the national economy out of necessity. Civil aircraft designs share common support equipment and facilities, which appear as indirect operational costs (IOCs) and do not significantly load aircraft pricing. The driving cost parameter for civilian aircraft design is the DOC, omitting the IOC component. Therefore, using a generic term of life cycle cost (LCC) = (DOC + IOC) in civil applications may be appropriate in context, but would prove to be off track for aircraft design engineers. Military design and operations incorporating discreet advances in technology necessarily have exclusive special support systems, equipment and facilities. The vehicles must be maintained for operation-readiness around the clock. Part of the supply costs and support costs for aircraft maintenance must be borne by manufacturers that know best and are in a position to maintain confidentiality on the high-tech defence equipment. The role of a manufacturer is defined in the contractual agreement to support its product for the entire life cycle of the aircraft "from cradle to grave" Here, LCC is meaningful for aircraft designers in minimizing costs for the support system integral to the specific aircraft design. Commercial transports would have nearly five times more operating hours than military vehicles in peacetime. Military aircraft have relatively high operating costs even when they sit idle on the ground. Academic literature has not been able to address clearly the LCC issues in order to arrive at an applicable standardized costing methodology. Aircraft design strategy is constantly changing. Initially driven by the classical subjects of aerodynamics, structures, and propulsion, the industry is now customer-driven and the design strategies consider the problems for manufacture/assembly that lead the way in reducing manufacturing costs. In summary, an aircraft engineer must be cost-conscious now, and even more so in future projects. Reference [20] addresses cost considerations in detail.

Aircraft design and manufacture are not driven by cost estimators and accountants; they are still driven by engineers. Unlike classical engineering sciences, costing is not based on natural laws; it is derived to some extent from manmade policies, which are rather volatile, being influenced by both national and international origins. The sooner the engineers include costing as an integral part of design, the better will be the competitive edge.

1.11 Units and Dimensions

The postwar dominance of British and American aeronautics has kept the use of the foot-pound-second system (FPS, also known as the Imperial System) current, despite the use of non-decimal fractions and the ambiguity of the word *pound* in referring to both mass and weight. The benefits of the Système International (SI) are undeniable: a decimal system and a distinction between mass and weight. However, there being "nowt so queer as folk," I am presented with an interesting situation in which both FPS and SI systems are used. Operational users prefer FPS (i.e. altitudes are measured in feet); however, scientists and engineers find SI more convenient. This is not a problem if one can become accustomed to the conversion factors. Appendix A provides an exhaustive conversion table that adequately covers the information in this book. However, readers will be relieved to know that in most cases, the text follows current international standards in notation units. Aircraft performance is conducted at the International Standard Atmosphere (ISA) (see Section 2.2). References are given when design considerations must cater to performance degradation in a non-standard day.

1.12 Use of Semi-empirical Relations and Graphs

DATCOM (US) and RAE DATA sheets (UK, recently replaced by ESDU) served many generations of engineers for more than a half century and are still in use. Over time, as technology advanced, new tools using computer-aided engineering (CAE) have somewhat replaced earlier methods. Inclusion of many of DATCOM/ESDU semi-empirical relations and graphs proves meaningless unless their use is shown in worked examples. It is important for instructors to compile as many test data as possible in their resources.

Semi-empirical relations and graphs cannot guarantee exact results; at best it is coincidental if they prove to be error-free. A user of semi-empirical relations and graphs must be aware of the extent of error that can incur. Even when providers of semi-empirical relations and graphs give the extent of the error range, it is difficult to substantiate any errors in a particular application.

If test results are available, they should be used in conjunction with the semi-empirical relations and graphs. Tests (e.g. aerodynamics, structures and systems) are expensive to conduct but they are indispensable to the process. Certifying agencies impose mandatory requirements on manufacturers to substantiate their designs with test results. These test results are archived as a databank to ensure that in-house semi-empirical relations are kept "commercial in confidence" as proprietary information. CFD and FEM are next in priority. The consistency of CFD in predicting drag has to be proven conclusively. At this stage, semi-empirical relations and graphs are used extensively in drag prediction as well as weight prediction.

Data reading from graphs is normal engineering practice, since graphs are readily available and data can be quickly obtained. But not all data are computerized (a good example is the general use of drag polar), and accuracy in reading data from graphs depends on their resolution. The graphs given in this book are small and do not have adequate resolution, therefore any readings are unlikely to be accurate. A good example will be shown in Section 9.9.1. It is recommended that the readers plot graphs with consistent accurate data in high resolution using high-end graph-plotting software.

1.13 How Do Aircraft Fly?

The mechanics of flight stems from the interaction between wind (air) and wing. A special property of air (gas) is the ability to generate lift through *wing–wind* interaction. Nature is conservative. Mass, momentum and energy in airflow is conserved unless there is an external intervention. Static pressure of the system is a form of energy (potential), and velocity is its kinetic energy. Together, the total energy is conserved – if one is changed, then the other is affected. For example, if velocity is increased, then its static pressure drops, and vice versa. This phenomenon is expressed as Bernoulli's Theorem.

A typical bread-slice-like wing section is known as an aerofoil, and its upper surface is more curved than the lower surface. Therefore, airspeed over the wing is faster (reducing its static pressure) than across the lower surface, resulting in a pressure difference directed upward. A sized wing area at a particular speed needs to generate requisite force (lift) to keep an aircraft in sustained flight. There is a minimum aircraft speed (stall speed) below which the wing will stall and will not develop sufficient lift. More details are given in Chapter 2. The entire subject matter comprises flight mechanics and its associated aerodynamic theories.

1.13.1 Classification of Flight Mechanics

The subject of flight mechanics may be divided into four subtopics:

1. **Performance:** The study of how an aircraft performs in terms of its kinematics, which is dependent on aerodynamic characteristics such as lift, drag and moments, and engine characteristics. It involves estimation of the extent of aircraft capability, which can be divided broadly as follows:
   - **a.** Point performance: the aircraft capability at an instant, involving rate capabilities (e.g. speed, climb rate, descent rate, turn rate, etc.).
   - **b.** Integrated performance: the aircraft capability integrated over a time period (e.g. takeoff and landing field length, climb to height, descent, mission range, etc.).
2. **Static stability:** The study of the tendency of the aircraft to remain in steady level flight when slightly perturbed. This leads to the prediction of the control movements and control forces required to change airspeed or load factor. This in turn leads to the idea of *handling qualities*. Longitudinal static stability is introduced in Chapter 6, as this affects aircraft performance.
3. **Dynamic stability:** The study of the motion of the aircraft after it has been disturbed in some fashion. The motions are classically divided into *modes of motion*, and the characteristics of the modes of motion are used to predict the flying qualities of the aircraft. Some modes are more important than others. The five classical modes are described in Chapter 6, but not treated in this book.
4. **Control:** The study of the effect of controls on the flying characteristics of the aircraft. Control is not dealt with in this course. It is treated as a separate subject.

The topic of this book is the first: the performance of aircraft. Aircraft design characteristics influence performance, and so their study is an integral part of understanding performance.

1.14 Anatomy of Aircraft

The study of aeronautics requires familiarity with aircraft configuration and the relevance of its components. The conventional aircraft configuration can be decomposed into the following eight sections.

1. **Fuselage:** This might crudely be regarded as the part of the aircraft that performs the function for which the aircraft was designed – carrying passengers, freight, electronic communications or munitions.

2. **The main wing:** The wing generates most of the lift required for flight. *Dihedral angle* or *sweep* on the wings provides *lateral (roll) stability*. *Flaps* on the trailing edge operate in sympathy and are used to enhance the lifting ability of the wing at low airspeeds. *Leading edge slats* and *wing spoilers* might be found on more complex wings.
3. **Ailerons:** These outboard flaps operate differentially and are used to control the roll rate of the aircraft. (See below for a little more detail.)
4. **Empennage:** The empennage comprises the horizontal (*tailplane*) and vertical (*fin*) surfaces at the rear of the aircraft.
5. **Tailplane:** The tail plane provides *longitudinal* (*pitch*) *stability*. The *elevator* is the flap on the tail plane and is used to control the aircraft in pitch. The *trim tab* is a small flap on the trailing edge of the elevator; it is used to balance the aerodynamic loads on the elevator in order to reduce the effort required of the pilot to maintain airspeed.
6. **Fin:** The fin provides *directional* (*yaw*) *stability*. The flap on the fin is called the *rudder* and is used to control the sideslip angle of the aircraft.
7. **Powerplant:** The power plant provides the thrust that balances the drag of the aircraft. Without the power plant, the aircraft is a glider. Power plants may be piston-props, turboprops or turbofans (see Chapter 4).
8. **Undercarriage:** The undercarriage or landing gear allow for safe operations on the ground (taxiing, takeoff, landing).

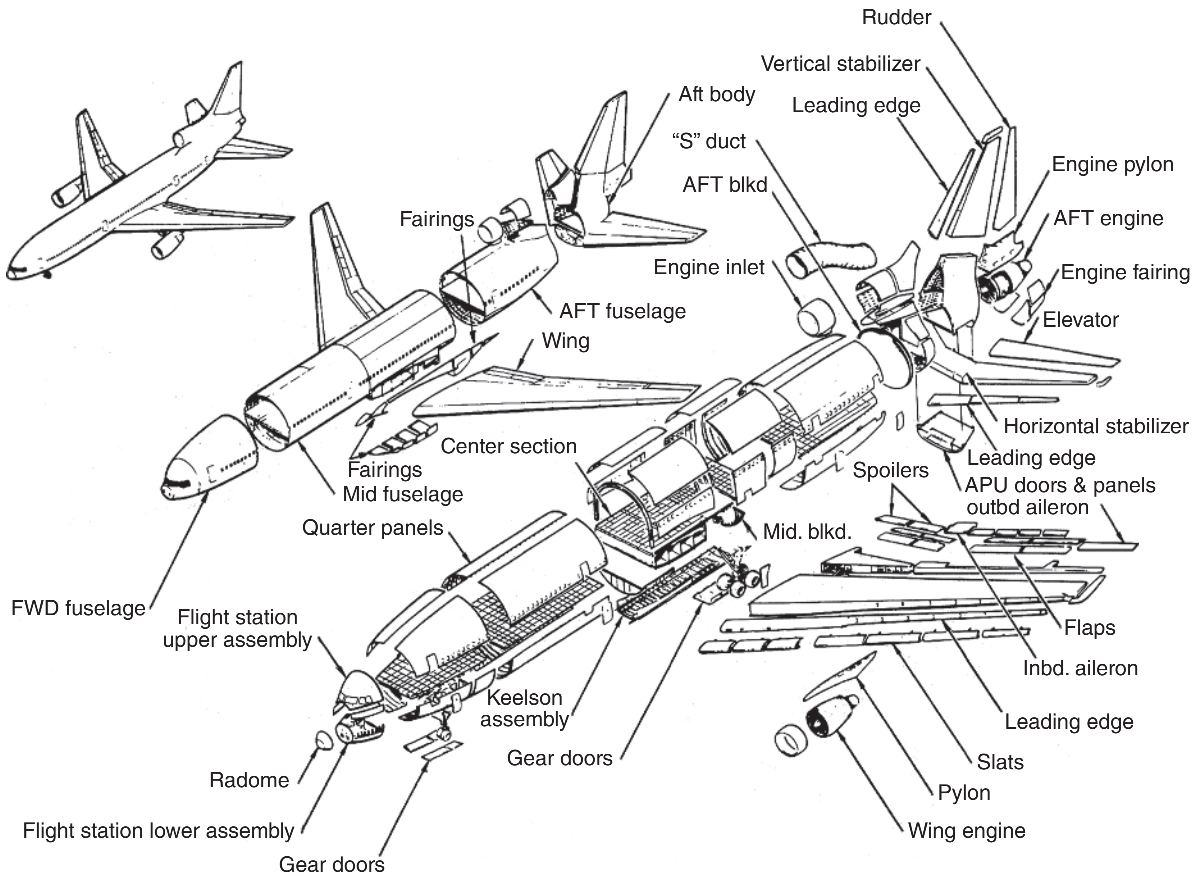
Both civil and military aircraft have different categories of design to cater for specific mission roles, and therefore aircraft performance capabilities will show wide variation. Section 10.4 describes in detail the various types of mission profiles for both civil and military aircraft.

The typical aircraft components of large aircraft are shown in Figure 1.15. The obvious components are generic (e.g. wing, fuselage, nacelle, empennage, control surfaces, etc.) for all types. Less obvious ones are typically winglets and strakes, but they play vital roles – otherwise they would not be there. There are many options. For convenience, components are associated in groups as described below. Not shown in the figure are the trimming surfaces used to reduce control forces experienced by the pilot.

Fuselage group: This starts with the nose cone, and then the constant mid-section fuselage, followed by the tapered aft fuselage, and at the end is the tail cone. The fuselage belly fairing (shown in Figure 1.15 as several sub-assembly components below the fuselage) may be used to house equipment at the wing–fuselage junction, such as the undercarriage wheels.

Wing group: This comprises the main wing, high lift devices, spoilers, control surfaces, tip devices and the structural wing box that passes through the fuselage. High lift devices include leading edge slats or trailing edge flaps; in Figure 1.15, the leading edge slats are shown attached with the main wing but the trailing edge flaps and spoilers are shown detached from the port wing. Spoilers are used to decelerate aircraft on descent and as the name suggests they spoil lift over the wing and are useful as "lift dumpers" on touchdown; thereby the undercarriage more rapidly absorbs the aircraft's weight, allowing more effective application of brakes. In some aircraft, small differential deflections of spoilers with or without the use of ailerons are used to stabilize aircraft rolling tendencies in disturbances. The wing is shown with winglets at the tip: winglets are one of a set of tip treatments that can reduce the induced drag of the aircraft.

Empennage group: The empennage is the set of stability and control surfaces at the back of the aircraft. In Figure 1.15 it is shown as a vertical tail split into the fin in front and the rudder



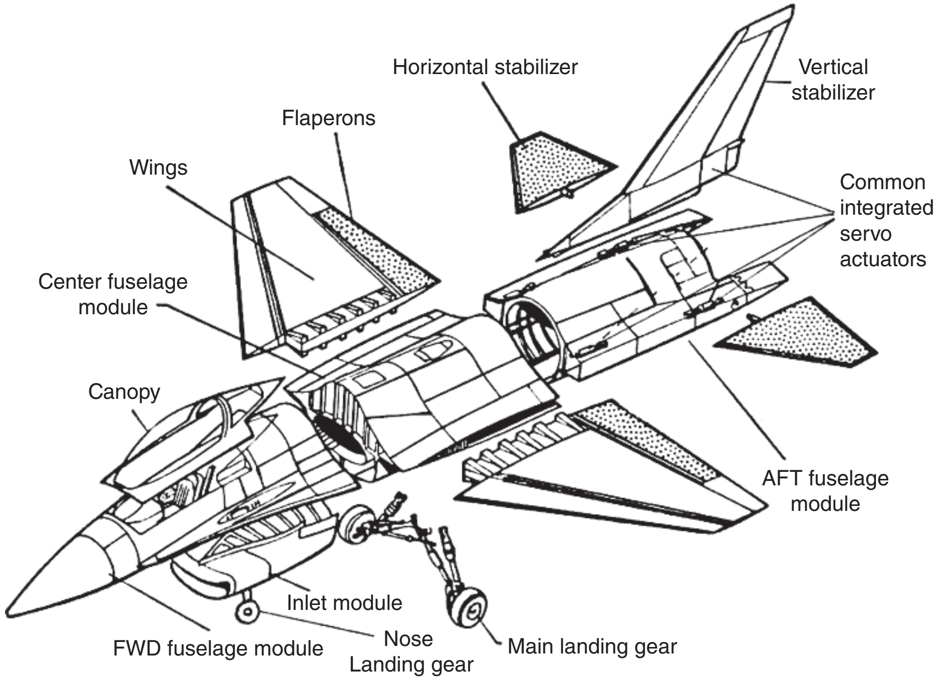
■ **FIGURE 1.15** **Lockheed 1011 (courtesy of Michael Niu [20], reproduced with permission of Commlit Press)**

at the back, and an end cap on the top; the horizontal tail, shown as a T-tail set at the top of the vertical tail, comprises the stabilizer and the elevator.

Nacelle group: The podded nacelles are shown mounted on either side of the aft fuselage; pylons effect the attachment.

Undercarriage group: Undercarriage, or landing gear, usually comprises a nose wheel assembly and two sets of main wheels, forming a tricycle configuration. Tail dragging, bicycle and even quad configurations are possible, depending on the application of the aircraft. Wheels are usually retracted in flight, and the retraction mechanism and stowage bay all form part of the undercarriage group.

Military aircraft statistics and geometric details need to be looked at differently on account of the very different mission role. Combat aircraft do not have passengers and the payloads have wide variation in armament type to carry internally and/or externally. Military configurations are more diverse than civil designs. Figure 1.16 shows a blowout diagram for the General Dynamics (now Boeing) F16. The component groups are similar to what is described above, except modern fighters do not have nacelles as the engine is housed inside the fuselage.



■ **FIGURE 1.16** **Military aircraft configuration (courtesy of Michael Niu [20], reproduced with permission of Commlit Press)**

However, in this book a military trainer of the class of RAF Hawk is dealt with. An example of an advanced jet trainer (AJT) with close air support is worked out as a military trainer aircraft performance, greatly simplifying the objective on military aircraft design.

Military aircraft carry mostly externally mounted combat equipment and weaponry, which would affect aircraft performance.

1.14.1 Comparison between Civil and Military Design Requirements

This section compares the two classes of aircraft design: civil and military (Table 1.5). It can be seen how different military aircraft design is compared with civil design.

Readers should consider what might be the emerging design trends within each class of aircraft. In general, new commercial aircraft designs are extensions of existing designs incorporating proven newer technologies (some are fallouts from declassified military applications) in a very conservative manner. Currently, dominant aerodynamic design trends show diminishing returns on investment. Structures technologies are seeking the introduction of suitable new materials (composites, metal alloys, smart adaptive materials) if these can reduce cost and/or weight (or aerodynamic gains). Engine design is still showing aerodynamic improvements to save fuel burn and weight.

1.15 Aircraft Motion and Forces

An aircraft is a vehicle in motion; in fact, it must maintain a minimum speed above the stall speed. The resultant pressure field around the aircraft body (wetted surface) is conveniently decomposed into a usable form for the designers and analysts. The pressure field alters with changes in speed, altitude and orientation (attitude). This book deals primarily with a steady

■ **TABLE 1.5**
Comparison between civil and military design requirements

Issue	Civilian aircraft	Military aircraft
Certification standards	Civil (FAR – US)	Military (Milspecs – US)
Operational environment	Friendly	Hostile
Safety issues	Uncompromised No ejection	Survivability requires ejection
Mission profile	Routine and monitored by ATC	As situation demands and could be unmonitored
Flight performance	Near steady-state operation and scheduled Gentle manoeuvres	Large variation in speed and altitudes – pilot is free to change briefing schedule Extreme manoeuvres
Flight speed	Subsonic and scheduled	Have supersonic segments; in combat unscheduled
Engine performance	Set throttle dependency No afterburner (subsonic)	Varied throttle usage With afterburner
Field performance	Mostly metalled runways generous in length with ATC support	Could have different surfaces with restricted lengths Marginal traffic control
Systems architecture	Moderately complex High redundancies No threat analysis	Very complex Lower redundancies Threat acquisition
Environmental issues	Strictly regulated – legal minimum standards	Relaxed – peacetime operation in restricted zones
Maintainability	High reliability with low maintenance cost in mind	Also with high reliability but at a considerable higher cost
Ground handling	Extensive ground-handling support with standard equipment	Specialized ground support equipment and complex
Economics	Minimize DOC Cash flow-back through revenue earned	Minimize LCC No cash flow-back
Training	Routine	Specialized and more complex

level flight pressure field; the unsteady situation is taken as transient in manoeuvres. Section 2.25 deals with certain unsteady cases (gusty) and reference will be made when occasion demands some design consideration. This section is primarily meant for information on some of the parameters concerning motion and force used in this book.

1.15.1 Motion – Kinematics

Unlike an automobile, which is constrained by the surface of the road, an aircraft is the least restricted vehicle, having all the six degrees of freedom (Figure 1.17) – three linear and three rotational motions along and about the three axes of any coordinate system. In this book, these are represented in the right-handed Cartesian coordinate system. Controlling motion in six degrees of freedom is a complex matter. Very careful aerodynamic shaping of all components of aircraft is of paramount importance, but the wing takes the top priority. Aircraft attitude is measured using Eulerian angles, ψ, θ and ϕ, which are treated in Chapter 4.

In classical flight mechanics, there are many kinds of Cartesian coordinate systems in use. Aircraft have a symmetrical shape, where the left side (port side) is a mirror image of the right side (starboard side). The X and Z axes are in the plane of symmetry (see Figure 1.17).

■ **FIGURE 1.17**
The six degrees of freedom of aircraft motion

■ **TABLE 1.6**
Summary of the components of the six degrees of freedom in the body-fixed coordinate system, F_B

Linear velocities:	u along X-axis (+ve forward) v along Y-axis (+ve right) w along Z-axis (+ve down)
Angular velocities:	p about X-axis, known as roll (+ve) q about Y-axis, known as pitching (+ve nose up) r about Z-axis, known as yaw (+ve)
Angular acceleration:	$\dot{p}$ about X-axis, known as roll (+ve) $\dot{q}$ about Y-axis, known as pitching (+ve nose up) $\dot{r}$ along Z-axis, known as yaw (+ve)

There are a few asymmetrical aircraft not treated here – they do not present any difficulty to analyse once the axes system is established. The three important kinds of axes systems are as follows.

1. **Body-fixed axes, F_B**, is a system with its origin at the aircraft centre of gravity (CG) with the X-axis pointing forward, the Y-axis going over the right wing and the Z-axis pointing downwards. It is nailed to the aircraft, and normally the X-axis aligns relative to the aircraft zero lift line; for aircraft with a constant section fuselage it is convenient to keep the X-axis running parallel to the constant section. The body axes system F_B is nailed to the aircraft at its CG and is fixed (see Table 1.6).
2. **Wind axes system, F_W**, also has its origin at the CG with the X-axis aligned with the relative direction of airflow to the aircraft and pointing forwards; the Y and Z axes follow the right-handed system. The wing axes F_W is gimballed to the aircraft at its CG and can rotate about it. Wind axes vary corresponding to the airflow velocity vector in relation to the aircraft. Aircraft motion in the vertical plane or in the horizontal plane has the Z-axis in the plane of symmetry. If aircraft have both angle of attack and yaw angle then the Z-axis is not in the plane of symmetry. From the difference between F_B and F_W, the angles of attack (α), yaw (β), and roll (φ) can be established (see Figure 4.2).

3. **Inertial axes, F_I**, are fixed on the ground. For speed–altitudes below Mach 3 and 80,000 ft, the Earth can be considered as flat and not rotating with little error, so the origin of the inertial axes is pegged on the ground, with the X-axis pointing eastwards, which makes the Z-axis point vertically downward in a right-handed system.

If the parameters of one coordinate system are known, then parameters in other coordinate systems can be found out through transformation relationships.

1.15.2 Forces – Kinetics

In a steady-state straight level flight, an aircraft is in equilibrium under the applied forces (lift, weight, thrust and drag) as shown in Figure 1.18. This is the final outcome of the pressure field around the aircraft. Lift is measured perpendicular to aircraft velocity (free stream flow) and drag is opposite to the direction of aircraft velocity. In a steady level flight, lift and weight are opposite to each other. Opposite forces may not be collinear.

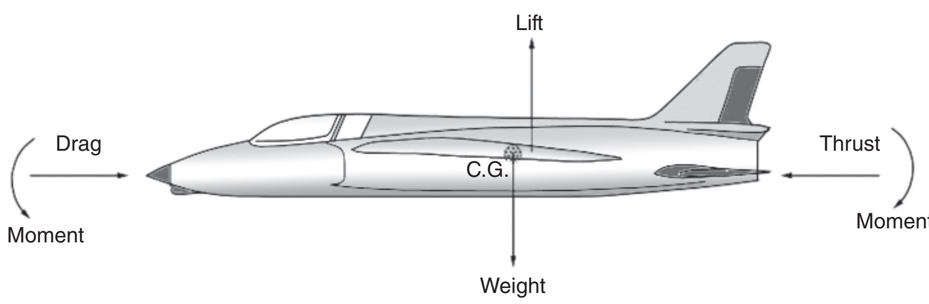
Forces and moments are associated with any body moving through fluid. In steady level flight in equilibrium, **Σ Force = 0**; that is, in the vertical direction, lift = weight, and in the horizontal direction, thrust = drag. In a steady-state straight level flight there is no side force.

The aircraft weight is exactly balanced by the lift produced by the wing (the fuselage and other bodies could share a small part of lift – to be discussed later). Thrust provided by the engine is required to overcome the drag arising from viscous, pressure and other forces.

Moments arising from various aircraft components are summed to zero to keep the flight level and straight; that is, **Σ Moment = 0**.

When not in equilibrium, the accelerating forces are taken into account at the instant of computation to find its resultant net force affecting the aircraft flight condition. If there were any force/moment imbalance, it would show up in the aircraft flight profile. That is how aircraft is manoeuvred – through force and/or moment imbalance – even for simple actions of climb and descent. The different axes systems are defined in Section 3.2. A summary of forces and moments in body axes F_B is given in Table 1.7.

■ **FIGURE 1.18**
Equilibrium flight



■ **TABLE 1.7**
Summary of the forces and moments in the body-fixed coordinate system, F_B

Axis	Force	Moment	Velocity component	Angle	Angular velocity component
x	X	L	U	φ	p
y	Y	M	V	θ	q
z	Z	N	W	ψ	r

In wind axes F_W the forces and moments are transformed to different magnitudes and directions where the force components X, Y and Z are resolved to lift (L), drag (D) and side force (C).

1.15.3 Aerodynamic Parameters – Lift, Drag and Pitching Moment

This section gives other useful non-dimensional coefficients and derived parameters frequently used in this book. The most common nomenclature, without any conflicts between both sides of the Atlantic, are listed here; these are internationally understood. (See Section 2.6 for the definition of aerofoil chord and Section 2.16 for the definitions of wing area S_W.)

$$q = ½\rho V_\infty^2 = \text{dynamic head}$$

The subscript ∞ represents free stream conditions and is sometimes dropped.

q is a parameter extensively used to non-dimensionalize lumped parameters.

The coefficients of 2D aerofoils and 3D wings differ as shown below (note that for the subscripts, lowercase letters represent 2D aerofoil cases and the capital letters are for 3D wings).

2D aerofoil section:

C_l = Sectional aerofoil lift coefficient = *Section Lift/qc*
C_d = Sectional aerofoil drag coefficient = *Section Drag/qc*
C_m = Aerofoil pitching moment coefficient = *Section Pitching Moment/qc*^{2} (+ nose up)

For wing (3D), replace chord *c* with wing area S_W:

C_L = Lift coefficient = $Lift/qS_W$
C_D = Drag coefficient = $Drag/qS_W$
C_M = Pitching moment coefficient = $Lift/qS_W^2$ (+ nose up)

Figure 3.12 gives the pressure distribution at any point over the surface in terms of pressure coefficient, C_p, which is defined as:

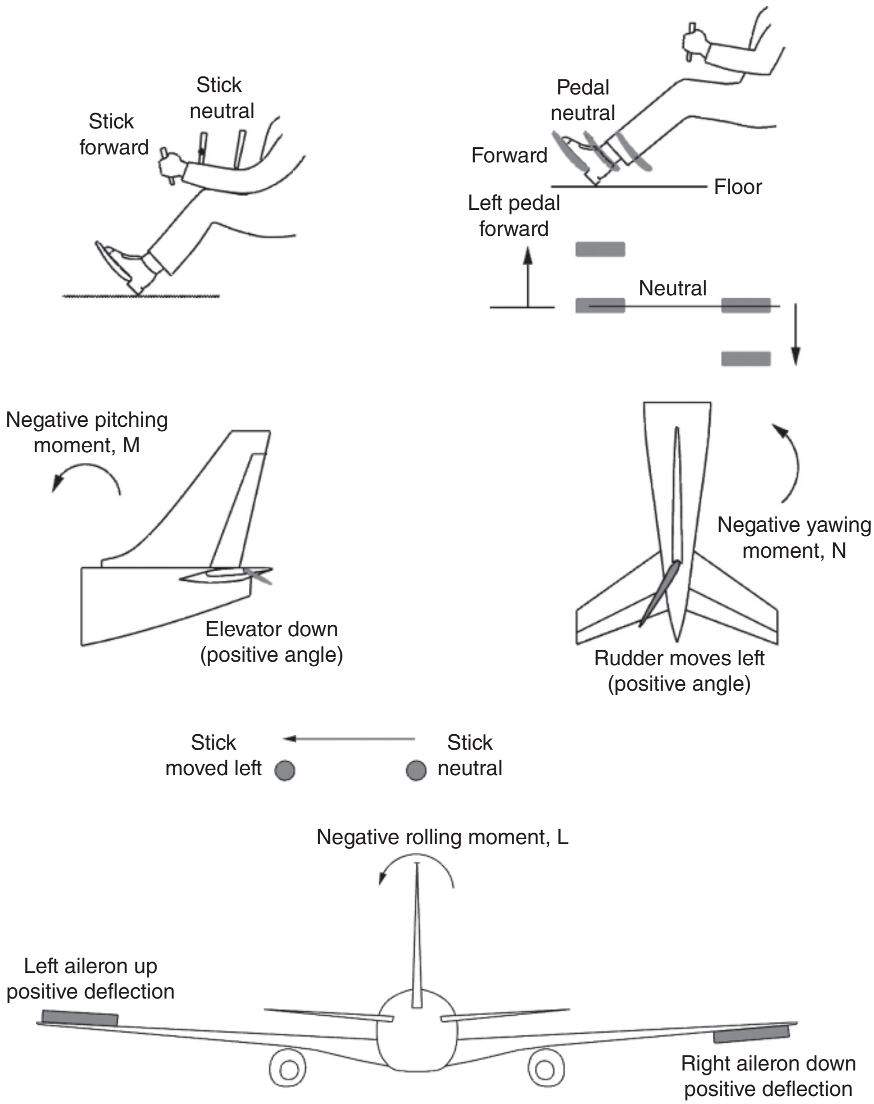
$$C_p = \left(p_{local} - p_\infty\right) / q$$

1.15.4 Basic Controls – Sign Convention

Conventional aircraft have four basic controls: the elevators, ailerons, rudder and throttle. The elevator and the throttle are longitudinal controls, in that they affect the three longitudinal degrees of freedom: changes of speed along the *Ox* axis; heave in the *Oz* direction; and pitch about the *Oy* axis. Likewise, the ailerons and the rudder are called lateral controls because they affect the three lateral degrees of freedom: sideslip along the *Oy* axis; roll about the *Ox* axis; and yaw about the *Oz* axis.

1. **Throttle:** The throttle is used to control the thrust of the engines of the aircraft. Its principal purpose is to control the rate of climb or descent of the aircraft.
2. **Elevator:** The elevator is used to control the angle of attack of the aircraft, and therefore its airspeed. Note that positive elevator angle, η, generates negative pitching moment, *M*, and that this is achieved by pushing the control column forward (Figure 1.19).

■ **FIGURE 1.19**
Control deflection and sign convention



3. **Aileron:** The ailerons are used to control the aircraft in roll. More specifically, the ailerons apply a rolling moment to the aircraft and so are used to demand *roll rate*. Roll rate is used to achieve bank angle, and bank angle is used to initiate a turn. Note that positive (right-hand side down) aileron angle, ξ, generates negative rolling moment, L (Figure 1.19).
4. **Rudder:** The rudder is used to control the side-slip angle of the aircraft. This might be of particular importance when landing in a crosswind. Rudder may also be used to *balance* a banked turn. Note that positive rudder angle, ζ, generates negative yawing moment, N.

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