Cambridge University Press
978-1-107-02400-7 - Advanced Aircraft Flight Performance
Antonio Filippone
Excerpt
More information

1 Prolegomena

Commercial aviation has grown to become the backbone of the modern transport system. Demand for commercial air travel has grown exponentially since the 1960s. The expansion of the aviation services is set to increase further. Even in the worst moments of recession, air transport has only suffered a blip in its expansion. Our global economy has become so dependent on air transport that any inconvenience caused by weather and external factors can cause mayhem. To understand the size of commercial aviation, reflect upon the fact that by the year 2000, there had been 35.14 million commercial departures worldwide, for a total of 18.14 million flight hours[1]. In some countries, air transport accounts for one quarter of all transported goods by value. It is estimated that there are about 50,000 airports and airfields around the world[2] and 18,000 commercial airplanes flying every day. A number of large airports are being constructed in some rapidly expanding regions. Modern airports are the size of a city: London Heathrow covers about 12 km^2; this is an area large enough to park about 1,800 Airbus A380s nose-to-tail. The support required by the aircraft is extraordinary and involves engineering, logistics, integrated transport systems, security systems, energy and people. However, at the heart of everything is the aircraft itself, interpreted as a flight system: this is the subject of our book. There will be only a superficial mention of various externalities, including air traffic control, queueing models, stack patterns, logistics, supply chains, and so on. More specifically, this book deals with the analysis, simulation and prediction of aircraft flight performance at several levels, including aerodynamics, weight performance, flight mechanics, aircraft noise and environmental emissions. Advanced aircraft performance analysis involves at least the following engineering activities:

- verification that an aircraft achieves its design targets
- efficient operation of existing aircraft or fleet
- selection of a new aircraft
- modification and upgrade of the flight envelope
- upgrading and extension of the mission profile
- aircraft and engines certification process
- environmental analysis, including emissions on the ground and in flight

Cambridge University Press
978-1-107-02400-7 - Advanced Aircraft Flight Performance
Antonio Filippone
Excerpt
More information

- aircraft noise emissions
- design of a new aircraft with and without optimisation methods

Note that in this list of specifications, only the last one involves the design of a brand-new aircraft, something often referred to as “conceptual design”. Safety in aviation dominates over everything else. Thus, health monitoring, adverse weather events and human factors become an integral part of operating an aircraft and maintaining safety records.

The methods used for the evaluation of aircraft performance are based on theoretical analysis and flight testing. The latter method is made possible by accurate measurement techniques, including navigation instruments.

Performance flight testing involves the calibration of instruments and static tests on the ground, testing at all the important conditions, gathering of data, data analysis, calibration with simulation models, determination of charts for the certification and the flight manual.

Performance analysis is based on the elaboration of flight data, either from flight testing or from flight data recorders. It is normally done at the operational level by commercial airlines in the attempt to determine how the airplane performs over time, in comparison with other airplanes and in comparison with the manufacturer’s claims. The complexity of the modern vehicle and the variability of all external factors contribute to changes in performance that often do not correspond to the technical specifications. Most manufacturers have their own flight performance codes tuned for their own aircraft.

Performance prediction is at the base of any concrete aircraft design and operation. The estimation of weights, range and power plant size requires the calculation of basic aircraft performance from a few input data. In this case the approximation is generally good enough for parameter estimation and design. A manufacturer claims (typically) that: its airplane has 20% lower direct operating costs (including −30% fuel consumption) than competitor X. How are we going to find out that this is the case? Do we buy one of its airplanes and one from competitor X? Do we spend 1,000 hours in flight testing and then decide? In the field of aircraft performance there is no laboratory experiment that can be used for verification.

1.1 Performance Parameters

Most of the aircraft flight parameters are stored by the Flight Data Recorder (FDR), commonly called the *black box* (although its colour is often orange). The set of data recorded is now standardised and contains all of the parameters that may be useful for accident investigation, systems monitoring, flight trajectory analysis and engine performance. As of August 2002, the National Transportation Safety Board (NTSB, United States) requires the records of at least 88 flight parameters for a transport category airplane.[3] These data include values for all the degrees of freedom of the aircraft, velocities, acceleration rates, controls positions and engine state (temperatures, pressures, fuel flow, rotation speeds), and quantities as different as computer failure, autopilot engagement, icing, traffic alerts and collision-avoidance systems. The requirements for large helicopters include records for at least 26 different flight

Cambridge University Press
978-1-107-02400-7 - Advanced Aircraft Flight Performance
Antonio Filippone
Excerpt
More information

and state parameters. An additional set of 30 parameters is recommended though not required.

Modern FDR, based on solid-state memory, can record several hundred parameters for up to 24 hours. They can withstand accelerations of hundreds of g-s, temperatures in excess of 1,000°, and survive in ocean depths of 6,000 m, whilst emitting a locator beacon for about 30 days. If ditched into the ocean, they can be located by satellite.

One of the most challenging recoveries was that of an FDR from an Airbus A330 that disappeared off the coast of Brazil on 1 June 2009. The FDR was eventually found intact, nearly two years later, 4,000 metres below sea level, after searching 10,000 km^2 of sea floor.

International regulations mandate that commercial operators of aircraft heavier than 27,000 kg have their FDR data monitored. In practice, it is required to analyse the flight parameters, particularly in cases when problems of any nature may occur (too steep descent rate, hard landing, flight through clear sky turbulence, and so on). The scope of this analysis is at least twofold: 1) to guarantee safety, and 2) to understand whether the aircraft is operated efficiently.

Many performance indexes cannot be simply expressed by a single value; they are presented with charts. Some performance data are readily available from the manufacturer, other data can be inferred by appropriate analysis, others are clouded by secrecy or confidentiality, and others are difficult to interpret because the conditions under which the aircraft performs are not provided. Among the most common data covered by secrecy are the drag data, the stability characteristics, the excess power diagrams and the engine performance. Other examples are 1) the aircraft range, when the payload is not supplied together with the range, 2) the altitude at which this range is achieved, and 3) the radius of action of a military interceptor. This radius, in fact, may lie in the field of enemy fire.

The maximum take-off weight (MTOW) and the operating empty weight (OEW) are available for most aircraft. However, these data are not sufficient to calculate the maximum payload because the difference between MTOW and OEW must include the mission fuel. A weight advantage compared to heavier rivals translates into significant revenue-earning advantages, which in a competitive market is the most important factor for choosing and operating an aircraft. It is not uncommon to find manufacturers unhappy that their performance data and charts are published in the public domain. Performance charts allow customers and competitors to look at various options, to select the most competitive aircraft and to discover the flaws of the competitors' technology.

The operator of an aircraft is concerned that the performance parameters quoted by the manufacturer match the actual performance, and therefore accuracy of performance prediction methods is essential. Performance data in the Flight Crew Operating Manual (FCOM) are not always accurate for a variety of reasons: 1) the FCOM data are often extrapolated from a limited set of flight test data, 2) the actual flight conditions are different from the conditions in the FCOM, and 3) ageing effects on the airframe and the propulsion system may lead to performance sensibly different from new aircraft. One aircraft type may have several FCOM because each airline may have its own version.

Cambridge University Press
978-1-107-02400-7 - Advanced Aircraft Flight Performance
Antonio Filippone
Excerpt
More information

1.2 Flight Optimisation

Flight optimisation is at the heart of design and operation of all modern aircraft. From the operational point of view, commercial aviation is driven by fuel prices, and operations at minimum fuel consumption are of great relevance. Performance optimisation requires notions of optimal control theory, a subject unfamiliar to the aerospace engineers. In the past 30 years these optimal conditions have been increasingly challenged by environmental concerns, including noise emission, air quality near airports, global climate change and sustainability.

Computer solutions of aircraft performance are now routine jobs and have reached a phenomenal level of sophistication to include the coupling among flight mechanics, aerodynamics, structural dynamics, flight system control and differential game theory.

There are two key types of optimisation: Optimisation of the aircraft performance during the design phase, and optimisation of the operational performance for the given airplane. In the former case, one can investigate the alternative changes in configuration that improve one or more performance parameters. This is more appropriately the subject of aircraft design. We will consider some cases of operational optimisation. An excellent source for optimisation problems with aircraft applications is the classical book of Bryson and Ho on optimal control[4] and Ashley[5] for a variety of flight mechanics problems. Today there are programs that plan optimal trajectory routes to minimise direct operating costs (DOC), whilst complying with several airline constraints. These programs have several types of input data: weather conditions, route, aerodynamics, aircraft performance and flight-specific information, such as payload, fuel cost, and so on. On output they provide the amount of fuel for optimal cruise altitude, climb and descent points, optimal cruise speed and flight path.

The flight controls themselves have reached a phenomenal level of sophistication, with several on-board computers and substantial software; they now represent a key aspect of the aircraft system. The best airplane cannot fly without its embedded software that satisfies the most stringent requirements. According to recognised standards – for example, NASA[6] – software controlling vehicles for human flight must have the highest level of quality assurance and is defined as *Class A*. Software failure in this class may cause a loss of life, or *catastrophic mission failure*. Next comes *Class B* software, which is designed for non-human flight: unmanned vehicles, rockets and satellites. Any software failure can lead to a total or partial loss of the vehicle but no loss of life (*partial mission failure*).

Figure 1.1 shows the flight control panel of the Gulfstream G550, with its peculiar four-screen view. The monitor display at the bottom centre of the photograph allows rapid performance calculation, including take-off speeds from basic input parameters, that can be quickly programmed by the pilot.

1.3 Certificate of Airworthiness

The certificate of airworthiness is a document that grants authorisation to operate an aircraft. It specifies the type of operations; the limits of operation of the vehicle in terms of weights, take-off and landing requirements; and a number of other

Cambridge University Press
978-1-107-02400-7 - Advanced Aircraft Flight Performance
Antonio Filippone
Excerpt
More information

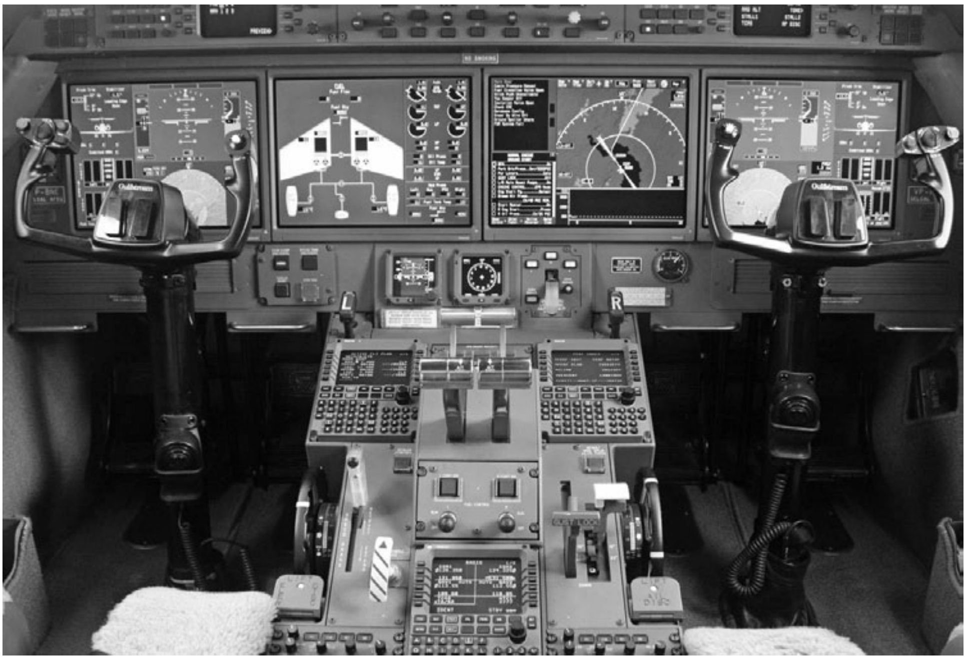

Figure 1.1. Cockpit of the Gulfstream G550 with Honeywell DU-1310 visual displays (author's photograph).

parameters, such as maintenance records, service history and compliance with safety regulations.

The certificate proves that the aircraft conforms to the type specified and it is safe to fly. The certificate is valid as long as the aircraft meets the type specification (commercial, commuter, utility, and so on), it is operated safely and all the airworthiness directives are met. The aircraft may lose its certificate for a number of reasons, including modifications upgrades and new directives approved by the international organisations that make the aircraft obsolete, not just unsafe to operate. Other documents are generally required, such as the type certificate data sheet, the airworthiness limitations, the flight log book, the certificate of maintenance and a list of other papers. The airworthiness limitations contain specific data on the number of flight hours, years of service or number of cycles for critical components and systems. These data can be used as limiters in flight simulation programs.

The *type certificate* contains various technical data, limitations and cautions, as well as reference to the appropriate technical manuals (operating manuals, maintenance manuals, and so on). Separate type certificates are issued for aircraft, propellers and engines. These certificates are issued by various national and international aviation organisations and are sometimes a duplication of effort in different countries. These certificates, which can run to several pages, contain at least some of the following data: airworthiness category, engines, engine limits, fuel, limit speeds, centre of gravity range, maximum certified weights, auxiliary power units, equipment, seating capacity, all weather capabilities and so on.*

---

* For example: European Aviation Safety Agency, Type Certificate Data Sheet, Airbus A380. TCDS A.110, Issue 04, Feb. 2009.

Cambridge University Press
978-1-107-02400-7 - Advanced Aircraft Flight Performance
Antonio Filippone
Excerpt
More information

Certificates of airworthiness and the type certificates are issued by the Federal Aviation Administration (FAA) in the United States, the European Aviation Safety Agency (EASA) in Europe, the Civil Aviation Authority (CAA) in the United Kingdom and other national and international bodies around the world. Certification is a complex legal and technical matter that falls beyond the scope of this book. Note that the certificates issued by different bodies may contain different types of information. Therefore, it is sometimes useful to obtain the different certificates, particularly when mining for engine performance data.

1.4 The Need for Upgrading

Most aircraft performance applications focus on performance for design, performance optimisation and aircraft sizing. It seems naive to forget that more than 18,000 commercial airliners fly around the world every day. The same airlines will be flying for the next 20 years, as businesses try to recover their capital investments.

How many aircraft are actually sized every year? Most aircraft are likely to be upgraded and modified to fit the changing market and technological advances. The technology that is fitted over the years can be phenomenally different from the first design. The service time of a single aircraft is on the order of 20 to 25 years, and the life of an aircraft family may exceed 50 years. A single airplane program consists of several versions, derivatives, design improvements, weight configurations, power plants, avionics and systems.

A life-time career can be devoted to a single airplane. In the early days of aviation, a new aircraft could roll out of the factory in a few months. In 1936, it took just one year for the German aircraft designer Kurt Tank[7] to get from concept to first flight of the Focke Wulf Condor Fw-190, the first long-range passenger (and later reconnaissance and bomber) aircraft to fly from Berlin to New York without en-route stop (in 1938). By the 1960s, commercial airplane design and testing required thousands of man-years. The Boeing B747-100, that first flew in 1969[8;9], required 15,000 hours of wind-tunnel testing and about 1,500 hours of flight testing with five aircraft[1].

The B747-400 incorporated major aerodynamic improvements, including a more slender wing with winglets to reduce drag. A weight savings of approximately 2,270 kg was achieved in the wing by using new aluminium alloys. The version B747-400ER has an increased take-off weight of 412,770 kg. This allows operators to fly about 410 nautical miles (∼760 km) farther or to carry up to an additional 6,800 kg payload, for a range up to 14,200 km (∼7,660 n-miles). A larger version of this airplane, the B747-800, weighing about 443 metric tons, is due to carry on the 747-flag for many years to come.

An even older airplane is the Lockheed Hercules C-130A. Its first model was delivered to the U.S. military in 1956. The design of this aircraft actually started several years earlier. By the early 1960s, a VSTOL variant was designed[10]. Since then, the aircraft has progressed through at least 60 different variants. The version C-130J is actually a new airplane. Compared to the earlier popular version C-130E, the maximum speed is increased by 21%, climb time is reduced by 50%, the cruising altitude is 40% higher, the range is 40% longer and its Rolls-Royce AE-2100DE engines generate 29% more thrust, while increasing fuel efficiency by 15%. With new engines and new propellers, the C130-J can climb to 9,100 metres (∼28,000 feet) in 14 minutes.

Technological advances in aerodynamics, engines and structures can be applied to existing aircraft to improve their performance. Over time weights grow, power plants become more efficient and are replaced, aerodynamics is improved by optimisation, fuselages are stretched to accommodate more payload and additional fuel tanks are added. Within the first few years of the Airbus A380 rolling out of the factory for the first time, new landing gear brakes design saved the weight of one passenger. At the same time, the wing was made about 350 kg lighter.

1.5 Military Aircraft Requirements

Military aviation has been a key aspect of national security since the very beginning of airplane engineering and is the source of many technological innovations. The fighter aircraft has evolved from a reconnaissance airplane of the First World War to the most complex aircraft of the modern day. Von Kármán[11] reported that they first flew over the battle fields of Europe to spy on enemy lines. Then enemy aircraft wanted to prevent this from happening, and hence their pilots started shooting at enemy aircraft with a pistol.

From reconnaissance to air strikes the step was short. The first recorded air bombing is attributed to the Italian Air Force during its Turkish Wars in North Africa in 1911–1912. The Italians operated a number of aircraft for reconnaissance (Taube, Deperdussin, Bleriot) but then started shooting at enemy forces on the ground. Finally, on 1 November 1911, they decided to drop four grenades weighing about 1.5 kg each. Lieutenant Giulio Gavotti carried out the air strikes in a Taube airplane[†]. Because the activation of the grenade required two hands and one hand was needed to steer the unstable airplane, the weapons were activated by snatching the plug with the teeth; then they were thrown overboard. Although the first bombs did not kill anybody (the blast was absorbed by the desert sand), the news was sensational. The Hague Convention (1899) prohibited the launching of projectiles and explosives from balloons. The Italians argued that the Convention did not apply to the powered airplane[‡]. Thus, the event was heralded as the start of a new era in warfare.

General Giulio Douhet was the first to distinguish among indiscriminate bombing, carpet bombing and strategic bombing (1912). In due course, the Germans used Zeppelin airships for the indiscriminate bombing of London in 1914 (the first urban bombing). The Hague Convention did not apply to them either. In response, the newly established Royal Air Force (RAF) performed the first air bombing of land targets with airplanes transported by ship near the theatre of war (Cuxhaven raid).

The psychosis of aerial bombing was sparked in the United Kingdom by H.G. Wells, who in 1907 published a science fiction book, *The War in the Air*, in which a

---

[†] Some sources report that the grenades were used for the first time on 24 October 1911 and landed on the desert; the day after the first casualty was recorded.

[‡] The Hague Convention, signed on 29 July 1899, entered into force on 4 September 1900. Chapter IV, in fact, limited the use of explosives from the air for five years, starting in 1900, by *balloon or other new methods of similar nature*.

Cambridge University Press
978-1-107-02400-7 - Advanced Aircraft Flight Performance
Antonio Filippone
Excerpt
More information

fleet of airships attacked and bombed New York City. The Americans were not impressed but years later, science fiction turned into reality, with great loss of life.

Following the operations in North Africa in 1911, the scope of military reconnaissance was considerably expanded: now it was possible to observe from above, to provide aerial photography and update and improve maps with unprecedented details. By the start of the First World War, reconnaissance aircraft had two seats, one for the pilot and the other for an observer – without which the pilot would have had difficulty returning to base. The observer's equipment included a map, a pistol, a watch, a pair of binoculars, a one-way radio system and a life vest. Typically, the useful load was around 400 kg, including pilot, observer and their equipment. If we allow for about 180 kg for all this weight, there was about 220 kg left, to be shared between fuel and ordnance. The fuel flow was of the order of 32 kg per flight hour. Without ordnance, an airplane would have been capable of an endurance of 6.5 hours. At an average speed of 100–120 km/h (∼50–60 kt), the radius of action would have been 350 km (∼190 n-miles) in the most optimistic scenario.

In 1915, during the early days of the war, the Dutchman Anton Fokker[12], working at the service of the German Army, invented a system that synchronised the shooting of a machine gun through the propeller (*interrupter gear*) – mounted on a single-seater monoplane. With the interrupter, pilots had hands free to manoeuvre and fight at the same time. Occasionally the interrupter malfunctioned and claimed the life of such accomplished pilots as Max Immelmann.

By the end of the Great War, the European powers had thousands of aircraft at their disposal. It has been estimated that the total production of such aircraft exceeded a staggering 75,000 units in four years, 32,000 of which were British; note that only 15 years had passed since the invention of the airplane.

To follow the history of the development of the military aircraft means following the development of key aeronautical technologies over the past 100 years. Two relevant books on the birth of military airplanes are Driver[13] (on the British aviation) and Opolycke[14] (on the French aviation). Stevens[15] and Weyl[16] report more generic historical details. Jackson[17] published a chronology of events recording aerial warfare from the very beginning to the present.

The requirements for fighter aircraft now include multi-purpose missions, aircraft with complex flight envelopes, several configurations (changeable in flight), supersonic flight, combat capabilities, delivery of a wide range of weapon systems, manoeuvrability, all-weather and night-and-day operations. The aircraft has become a platform system of phenomenal complexity and cost. Yet history deserves another revolutionary weapon system: the military aircraft of the future is unmanned. Nevertheless, there will be a few decades before this happens. In the meantime, there can be problems of excess capacity coupled with excessive costs, which in turn make the military aircraft difficult to sell, operate and upgrade.

There are dozens of different mission scenarios[18]. Typical missions are basic, assault, combat, retrieval, close support, transport, refuel and reconnaissance. For each of these missions there is a specific take-off weight, mission fuel, payload, range, maximum rate of climb and service ceiling. This field is now so advanced that engineers use differential game theory and artificial intelligence to study the effectiveness of a given aircraft and the tactical manoeuvrability to incoming threats[19].

1.6 Review of Comprehensive Performance Programs

This review is limited to computer models that are documented in the open literature[20]. Both Airbus and Boeing have their own flight performance programs that model their own aircraft by using a combination of first principles and extensive flight data. These programs are not in the public domain. Versions of these programs are provided to airline operators in order to facilitate their performance analysis and their flight planning.

Computerised flight planning goes back to the late 1960s. One of the first attempts was due to Simpson *et al.*[21], after it was recognised that the optimal route selection across the North Atlantic could lead to considerable fuel savings. The method required to take into account the actual state of the atmosphere (specifically, winds and temperatures). The analysis required some basic performance data for the aircraft, such as climb and descent programs, cruise altitude, fuel consumption and other parameters. Climate-optimal routing problems have remained topical to this day[22].

Roskam's Advanced Aircraft Analysis (AAA) modules are based on Roskam's books[23]. These performance modules focus on aircraft design, from weight sizing to aerodynamic prediction, control and stability analysis. Another code in this technology area is ACSYNT, whose origins go back to the 1970s. In recent years this code has undergone major development to adapt it to aircraft conceptual design. The code integrates various disciplines, including performance, design, costs, noise and engineering process[24;25]. A flight optimisation system called FLOPS was developed in the 1980s[26] to address detailed performance during preliminary design.

The program DATCOM[27] provides calculations on static stability, high-lift performance, aerodynamic derivatives and trim conditions of the aircraft at subsonic and supersonic speeds. The program has been used extensively for the rapid estimation of the static and dynamic characteristics of high-performance aircraft in the preliminary design stage. The approach followed by this method is accurate enough for several applications[28].

A comprehensive performance simulation that is used for the air-traffic management is the so-called BADA Model, developed at Eurocontrol. BADA uses the lumped-mass approximation, a total energy model for the centre of gravity and a basic performance model for the prediction of the aircraft trajectory[29;30]. Its main application is the prediction of flight trajectories in terminal-area manoeuvre and for a management of traffic at the current conditions and at forecast growth. The basic equations used by BADA are ordinary differential equations for the centre of gravity and the total energy equation (i.e., balance among kinetic energy, potential energy and work done by the engines). Additionally, the model uses integral values of the essential parameters of the aircraft, such as operational limits (from the flight manual or other sources).

The total energy concept has been used[31] to predict the fuel consumption of transport aircraft, without having to rely on statistical databases. This approach has already been used in the 1980s by the FAA to provide a better automatic flight planning for air traffic control. In principle, the method is quite powerful because it does not require many details of the aircraft. In fact, it relies on the fundamental energy balance, on the gross weight and on the path profile of the aircraft.

CAMBRIDGE

Cambridge University Press
978-1-107-02400-7 - Advanced Aircraft Flight Performance
Antonio Filippone
Excerpt
More information

ESDU[32] provides a suite of programs to calculate the performance of fixed-wing aircraft, including flight performance, airfield performance and mission performance (block fuel for a transport aircraft and radius of action for a military aircraft). The program consists of an implementation of several derivations published as data units, some of which are briefly discussed and cited in this book.

A comprehensive performance program of industry standards is PIANO[33]. This program includes preliminary design options, a large database of aircraft models and a detailed mission-performance analysis module. The program does a wide range of performance calculations and it is shown to match closely the manufacturer's performance, although the technical details are not disclosed.

1.7 The Scope of This Book

The subject of this book is the operational performance of aircraft, with all of the issues surrounding technology evolution (aircraft and engine upgrades) as well as the environmental impact. In this context, operational performance falls between conceptual design of aircraft and airport operations, which rely on limited information on the aircraft.

We present relatively advanced cross-disciplinary topics. We aim to solve accurately problems such as the best cruise altitude, the best cruise Mach number, and the best climb and descent procedures. We deal with commercial aircraft powered by either high by-pass turbofan engines or propellers-turboprop. We also discuss high-performance aircraft (mostly for military use) that are capable of supersonic flight. These topics are mapped into a computational framework that consists of a number of comprehensive computer programs. One such program should be able to accomplish at least some of the following tasks:

- trajectory optimisation and route planning
- mission analysis and field performance
- environmental emissions and fuel costs
- airframe–engine integration
- thermo-physics and structural dynamics
- aircraft noise trajectories
- noise impact around airports
- systems analysis
- verification of performance data
- competition analysis
- trade-off and parametric studies

A flowchart of the computer program is shown in Figure 1.2. This chart shows the key aspects of the sub-models of the performance framework, as well as the major items and sub-items of engineering analysis. Each of these items is discussed in the following chapters.

The flowchart for a supersonic high-performance aircraft is similar to Figure 1.2. However, the noise and emissions are not simulated, and there is more