1 Introduction to Aircraft Aerodynamic Design

A scientist studies what is, whereas an engineer creates what never was.

Theodore von Kármán[1]

The successful aeroplane, like many other pieces of mechanism, is a huge mass of compromise.

Howard T. Wright, early British aircraft builder and designer

Preamble

The subject of this book, the aerodynamic design of aircraft, is an integral task within the entire aircraft design, and a prime focus is the shaping and lay out of the aircraft's lifting surfaces. Introducing the subject matter of the book, this chapter also conveys some appreciation for, and fundamental insight into, how and why wings evolve toward the geometric configurations we see in reality. An intrinsic characteristic of the development of a new type of aircraft is that it evolves from a *succession of design cycles*. This chapter describes and explains three of these cycles occurring in the early design process. As Theodore von Kármán implies, creativity lies at the heart of any engineering activity such as aircraft design. Belonging to the cognitive aspects of the human brain, creativity is not the realm of technology, but we do indicate how and where it enters into the three design cycles, and we encourage students to "think outside the box."

The fundamental aerodynamic quantities, lift and drag, are key to performance. Sizing the wing surface to the mission of the design is a crucial step in determining the baseline configuration, which then develops further in the succession of Cycles 2 and 3. This chapter introduces the tools, tasks, and workflows of the three design cycles and explains how computational fluid dynamics (CFD) and optimization procedures are involved, and it maps out where in the coming chapters each of these is treated in depth.

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1.1 Introduction

The prime task of the aerodynamics team in aircraft design is to suggest the aircraft's *flight shape* (i.e. the shape of its outer skin exposed to the airflow). But the overall shape of the aircraft must also reflect considerations such as structural integrity, weight, engine characteristics, and performance. We call this design process *configuration development*.

This chapter describes the aircraft development process and the role of aerodynamics, focusing on computational tools. In particular, we consider the iterations where a proposed aerodynamic shape is modified to better suit its requirements. Such a step can be approached and formulated as an optimization problem for which the computational multidisciplinary analysis and optimization (MDAO) tools clearly cross disciplinary boundaries, and these are in very rapid development as we write. The acronym MDAO is often shortened to MDO. This book is *not* about MDO in its entirety, but rather only the part that CFD plays within it. Examples are given on how the aircraft's mission requirements influence basic features such as the shape of the wing's horizontal projection: its *planform* (Figure 0.1).

The science of aerodynamics involves two apparently separate, but in fact related, studies. *Fundamental aerodynamics* is concerned with the qualitative and quantitative examination of air in motion – with its displacement, velocity, and acceleration. *Applied aerodynamics* concerns the physical forces exerted by air on the bodies immersed therein through the motion of the air relative to the body. There are four major questions to be addressed:

(1) How is the aerodynamic force created to keep an aircraft in the air, and how does this force *vary* with *shape*, *attitude*, and *speed*? This is the problem of *lift*.
(2) What is the propulsive force necessary to keep the aircraft moving through the air? This problem is associated with the air resistance or *drag*, which is fundamental to the general study of aircraft performance.
(3) How does the force and its distribution on the aircraft *vary* in *flight*? This is the problem of the stability and control of aircraft.
(4) How do the airloads during flight deform the airplane into the *flight shape*? This is the engineering field of (static) aero-elasticity.

Aerodynamics is seen by some as a branch of applied mathematics; others consider it largely an experimental subject. Mathematical analysis alone, however, is ineffective, as its necessary simplifying assumptions prove useful only in some situations, but they are invalid in others. On the other hand, to proceed only by experiment limits one's knowledge to very specific situations and inhibits the making of reliable predictions.

The aerodynamicist, therefore, needs good enough theories to combine both of these approaches, using analysis to deepen and extend their knowledge. Continuous experimenting is required to check the validity of the assumptions and to improve understanding of the physics. Answers are always to some extent approximate, and the conclusions drawn are often limited to certain classes of situations.

To the novice, this all becomes a mixture of engineering experience, with models being constructed by guidance from theory but completed by curve fits, all producing a forest of formulas, each with limited applicability. Indeed, the approaches to solutions range from mostly statistical and empirically based models to fully physics-based methods. The limits to applicability of the physics-based methods have been pushed back significantly by high-performance computing machinery and software for CFD. But these computational tools are, and will be for the near future, unable to solve problems through first-principles models that are universally valid for typical-flight Reynolds numbers. Thus, many assumptions are still made in applied aerodynamics to facilitate a computational approach, and the caveat above still stands. Analogy with medical science is appropriate here, where engineering experience in the field plays the role of *clinical experience*.

Theory of Ideal Fluids

Three simplifying assumptions about airflow that are very useful at times are as follows.

(1) *Incompressible* flow: The assumption that fluid density is constant leads to a major simplification: the thermodynamics decouples from the kinematics. This gives very good results, provided that the fluid velocity is not too great, but is totally invalid at high speeds.
(2) *Inviscid* flow: Here, it is assumed that the viscosity of the fluid vanishes. A useful theory may be developed that gives good answers to the problem of lift. On the other hand, drag cannot be accounted for at all on this basis.
(3) *Irrotational* flow: Here, fluid particles do not rotate, being mathematically expressed as the vanishing of the vorticity of the velocity field $\omega = \nabla \times \mathbf{v}$.

Flow of an "ideal fluid" satisfies all three of these assumptions and leads to the d'Alembert paradox that the net force on a body vanishes. It would seem then to be completely useless, but the theory was modified and made into the Prandtl–Glauert wing flow engineering mathematical tool by Ludwig Prandtl and his followers.

1.1.1 Aerodynamic Design Is Part of Aircraft Design

The task of designing an aircraft is among the most complex in engineering. Not counting the smallest components such as nuts, bolts, and rivets, an aircraft may have hundreds of thousands of components, with over a million important design parameters and many more that are less important. Complex and advanced simulation and data management software systems are needed to support the design teams, both in the tasks each design team undertakes and for putting together the data and design parameters for the configuration as it evolves through (many) iterations and redesigns to arrive at a satisfactory solution. By the term *configuration* we mean the general layout and external shape, dimensions, and other relevant characteristics of the design.

Every aerospace company has its own structure and process for design, reflecting the diverse and complex nature of conceiving a new aircraft.

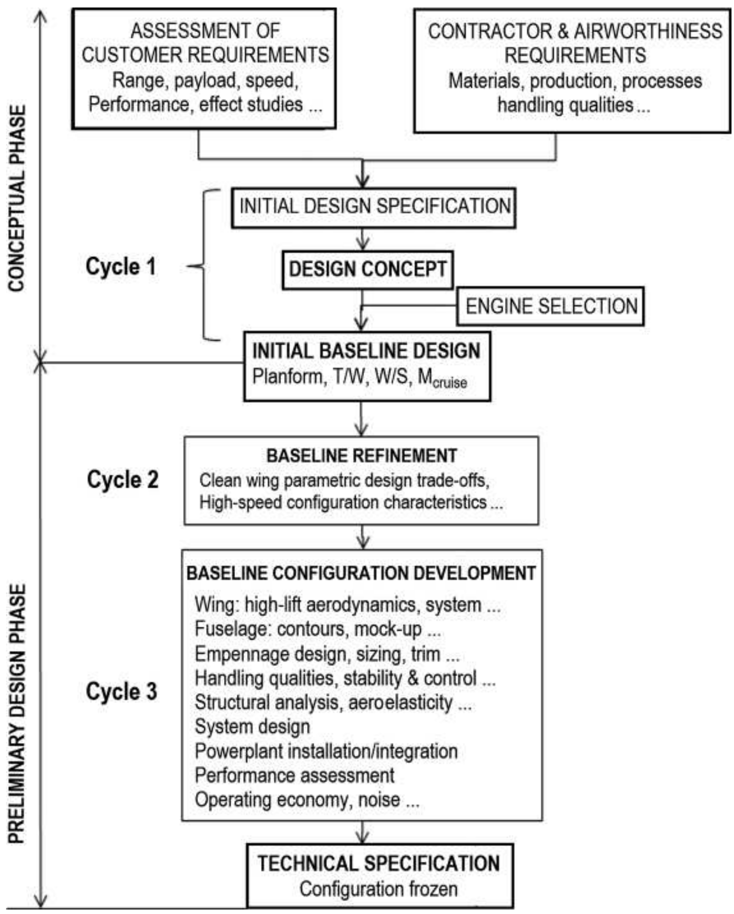

Figure 1.1 Configuration design and development of a typical transport aircraft evolving after a succession of Cycles 1, 2, and 3. (Adapted from Torenbeek [29], reprinted with permission)

For example, the preliminary design of the Boeing 777 was carried out by 3000 people. Coordination was facilitated through weekly design meetings of 25 lead engineers, each representing 100+ engineers in their specialty. Aerodynamic design is only one part of this vast enterprise.

There are a number of good textbooks on aircraft design (e.g. [19, 23, 29]) that spell out how the many disciplines work together to synthesize an aircraft in a process that is subdivided into conceptual, preliminary, and detailed design *stages*. Figure 1.1 presents a flowchart of the conceptual and preliminary design stages. It provides an overview of where and how aerodynamic design enters into the overall synthesis. The entire development of a new aircraft takes place in a *succession of design cycles*.

In the course of each of these cycles, the aircraft is designed in its entirety. Investigation is carried out into all of the main groups, airframe systems, and pieces of equipment to a similar level of detail. The extent of this detailing steadily increases as the design cycles succeed each other, until finally the entire aircraft is defined in every detail.

Using Torenbeek's [29] terminology, we further designate the subsequent basic design stages as follows.

(1) Cycle 1: conceptual design, also called speculative design, explores a large basic parameter space.
(2) Cycle 2: baseline refinement design, which demonstrates the feasibility of the speculative design.
(3) Cycle 3: baseline configuration development, which determines the best conceivable design among the feasible ones regarded as sufficiently mature. It finishes with the decision to freeze the configuration, ending the preliminary design.
(4) Detailed design comprises the final hardware design cycles of the configuration, which goes into production after flight-testing of prototypes. These cycles are beyond the scope of this book.

A number of aspects of the first three design cycles will be further elaborated and discussed in this book. The Cycle 1 conceptual design concludes with an initial baseline configuration, and this is covered in the present chapter. Chapters 8 and 9 present the Cycle 2 procedures followed in evolving an initial baseline configuration, and they constitute a major portion of this book.

Chapters 9, 10, and 11 present surveys of several topics related to the further Cycle 3 elaboration and development of the baseline configuration.

To give some idea of the magnitude of work in preliminary design, the initial baseline design of a transport aircraft will require several thousand person-hours. The subsequent design phase of variants and parametric studies will demand multiples of this effort.

Torenbeek [29] gives some idea of the scope of configuration development, citing the Lockheed L-1011 program. In the two years of its configuration development, over two million person-hours were expended on investigating various configurations and approaches in order to determine the optimum design.

Clearly, a textbook cannot hope to elucidate every aspect of what an aerospace company carries out. Instead, this text

(1) provides an overview of how modern software for analysis and optimization is used;
(2) outlines the mapping from shape to aerodynamic forces in some detail; and
(3) discusses the techniques and design tasks that can be carried out with academic software tools.

Hierarchical Breakdown of Aircraft: The Cayley Paradigm

Viewing the configuration as a hierarchy of its constituent components helps to manage the complexity of the design task, both in handling the design space (the set of design parameters) and in modeling its function.

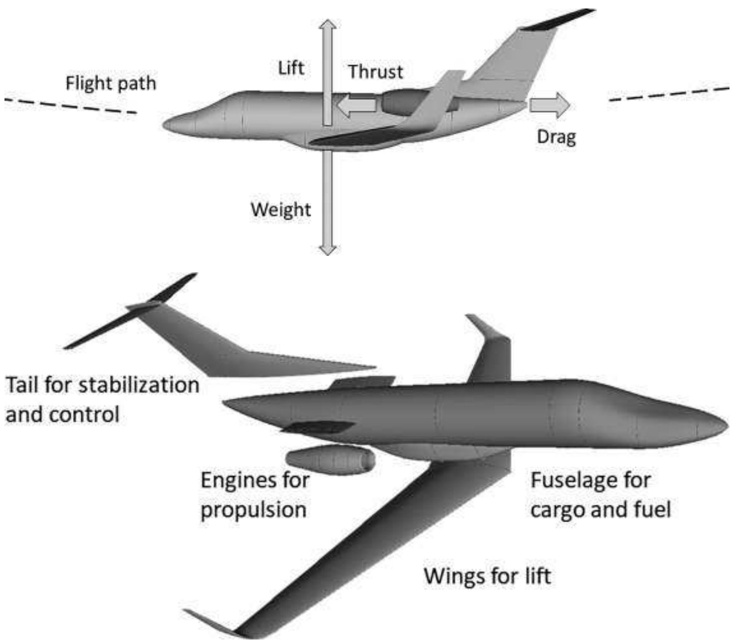

Figure 1.2 Forces in un-accelerated flight and aircraft components. (Top) Lift balances weight and thrust balances drag. (Bottom) Cayley's principle: each component of the aircraft has its distinct function.

The traditional hierarchical approach to design follows Sir George Cayley's design paradigm (see Figure 1.2, bottom). It assigns functions such as lift, propulsion, trim, pitch-and-yaw stabilization and control, etc., exclusively to corresponding subsystems such as the wing, the engine, the tail unit, etc. The top of Figure 1.2 shows weight (the gravitational force on the aircraft), which the lift must overcome, and drag, which must be balanced by thrust to stay aloft.

If these subsystems and their functions influence each other only *weakly* in well-understood ways, one is able to treat and optimize each subsystem with its functions more or less independently. Implicit in the paradigm is the decomposition not only of the subsystems and functions but also of the engineering disciplines into aerodynamics, structures, flight control, etc. This *decomposition* of the engineering disciplines has led to the established practice of *sequential and iterative design cycles*. However, the decomposition may limit the design space by neglecting potentially beneficial couplings between subsystems. If the design can be carried out with more concurrency between the design activities of the different teams, the number of design cycles can be reduced and the configurations can become more efficient. This is the goal of the MDO techniques enabled by high-performance computing.

1.1.2 Lift and Drag: Keys to Performance

When performance of the aircraft is discussed, the context is important: an airline executive looks at the bottom line in servicing the needs of the company's clients,

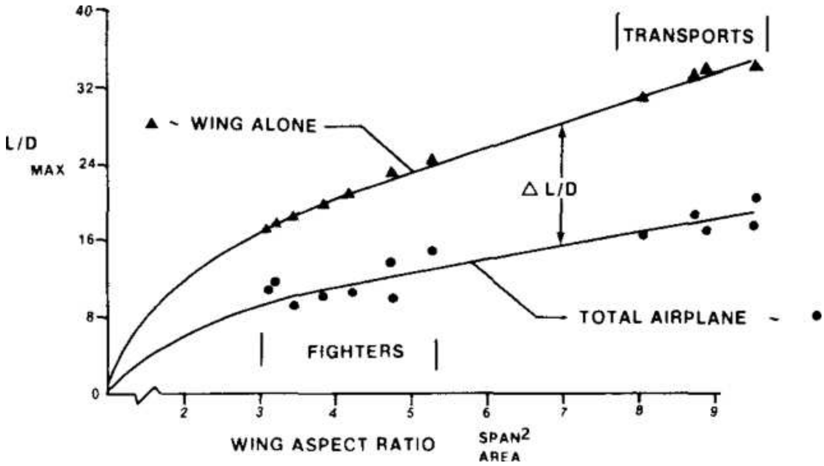

Figure 1.3 Maximum lift-to-drag ratio for total configuration and wing alone vs wing aspect ratio. (From Chuprun [3], AFWAL, public domain)

a stunt pilot is interested in quick response to control inputs, while top speed and turn rate are important qualities for fighter pilots. All performance metrics require data at least on airplane velocity and acceleration, and these must be derived from the forces exerted on the airplane by the surrounding air. While it is important to understand the airflow patterns, as discussed in Chapter 2, it is really only the resulting forces that matter for the aerodynamic designer.

1.1.3 Wings, Lift, and Drag

Wings provide lift that is much greater than their own weight. Fighter wings lift about 90 times their own weight, while for transport aircraft the ratio is about 22, where a prime focus is given to high cruise efficiency, hence maximum *lift-to-drag* ratio is the objective. In contrast to transport aircraft, fighters need high lift to maneuver at the expense of higher drag. Using data representative of modern fighter and transport aircraft [3], Figure 1.3 highlights the powerful leverage that wings possess in fulfilling their prime function of generating lift.

The plot in Figure 1.3 shows $(L/D)_{max}$ growing strongly with increasing aspect ratio. The wing contributes all of the lift and only half of the drag for the whole configuration, so its $(L/D)_{max}$ is about half of that of the total airplane. With some hyperbole, Chuprun coined the phrase “wing is king” in aircraft design, in the sense that the wing is the *backbone* of an airplane. Certainly, there is no heavier-than-air flight without aerodynamic lift. This fact also motivates why a flying wing, unburdened by the drag of other airplane components, potentially has high aerodynamic efficiency.

At its most elementary level, Figure 1.4 symbolizes and summarizes the description of the first steps in aircraft design. It also indicates the process that repeats itself in the subsequent cycles to further develop the design in more detail using an increasing number of parameters.

Table 1.1 Primary parameters for baseline planform design.

Planform	Area S
	Wing span b
	Aspect ration AR
	Taper ratio λ
	Sweep angle Λ
	Average thickness $(t/c)_{ave}$
Performance	Cruise Mach M_{cruise}
Propulsion	Thrust-to-weight ratio T/W
Structures	Weight-to-wing area ratio W/S

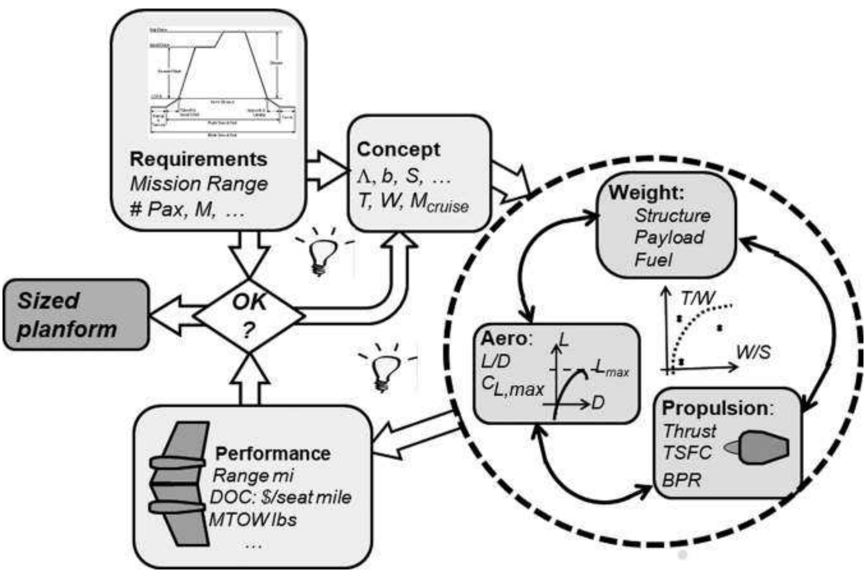

Figure 1.4 Initial sizing process in the Cycle 1 aircraft design process, with outcome of wing planform and size, showing the role of aerodynamics.

To start the process, the concept – usually hand-drawn – must be transformed into a geometry (i.e. its *flight shape* specified by a handful of primary parameters, such as those in Table 1.1).

That so many primary variables concern wing shape gives credence to Chuprun's claim that wing is king.

Specific Range

For most airplanes, range is one of the most important measures of performance. This is certainly the case for commercial aircraft, and for many military airplanes the maximum combat radius is of major importance. The differential form shown in Eq. (1.1) of Breguet's celebrated range equation relates the specific range SR of an aircraft in cruise (here, miles traveled per gallon of fuel at weight W) to properties of propulsion, weight, and aerodynamics:

$$SR = Const \underbrace{1/TSFC}_{engine} \quad \underbrace{ML/D}_{aerodynamics} \quad \underbrace{1/W}_{structure} \tag{1.1}$$

The equation is a simple consequence of the fact that, for steady flight at constant altitude, $L = W$ and $T = D$ (top of Figure 1.2), with M being the flight Mach number. The weight of the aircraft W diminishes as it burns its fuel. We see three important quantities:

(1) Choice of engine and its thrust-specific fuel consumption $TSFC$
(2) Total aircraft weight W
(3) Aerodynamic cruise efficiency $M\ L/D$

Measured in, for instance, $\frac{Gal}{N \cdot hr}$, $TSFC$ decreases when newer engines bring better fuel economy. For propeller propulsion, *power-specific fuel consumption* (= PSFC) is a more relevant measure across the speed range. Advanced materials allow for a lighter-weight aircraft structure. Equation (1.1) tells us that, to improve specific range, the *aerodynamic efficiency* $M\ L/D$ – the product of the flight Mach number (dependent on the planform) and the aerodynamic *quality* (the lift-to-drag ratio) – should be as high as possible.

Compound Benefits
Such improvements compound the benefits through interdependencies. If less fuel is needed for a given mission, the takeoff weight is reduced, less lift is required, so the wing area can be smaller (hence less drag), the cruise Mach can be increased, etc., in a virtuous circle. On the other hand, when weight *increases*, one unfortunately encounters the opposite: the vicious circle of compounding weight penalties rushing toward poorer performance.

For an innovative aircraft concept with better fuel efficiency, Eq. (1.1) points design efforts in the direction of a configuration with optimized aero-structural sizing to yield less weight and drag. Design represents the search for the optimization of these innovative aero-structural concepts for maximum aerodynamic and structural efficiency as well as safe and controlled flight during normal operation and in critical conditions.

1.1.4 Sizing the Wing Planform: Initial Parametric Design Cycle 1

The design process starts with the main mission requirements, desired performance, and cost goals, as Figure 1.4 suggests.

Requirements for commercial airline services follow from the analysis of the intended flight route, including data on expected traffic volume and desired frequency, typically between city pairs. This sets the desired payload-range characteristics.

The *performance* requirements would typically include factors such as maximum takeoff weight, start and landing distances, maneuverability, rate of climb, service ceiling, speed, fuel economy given a maximum size and weight, etc. In addition, the aircraft must be certified by regulatory authorities, which adds requirements that are discussed in more detail below and in Section 1.1.5.

Airworthiness Requirements

The suggested configuration must satisfy further conditions to ensure it is *airworthy* (i.e. can be operated with adequate safety in the air as well as on the ground). Airworthiness requirements govern performance, control, stability, trim, structural and mechanical design and a host of other aspects. Published by the International Civil Aviation Organization, the International Standards of the Chicago Convention (1944) spell out what is required for an aircraft in civil aviation to be deemed airworthy and certifiable by the regulatory authorities.

Structural design is of critical importance to aircraft safety and plays a key role in aircraft cost, weight, and performance. In addition, the aircraft structural weight affects performance through the compounding effect explained above. In order to predict the aircraft cost and empty weight, we must estimate the weight of each of the components. Thus, we need to calculate the loads that they will have to support in flight and on the ground, wing bending moments due to aerodynamic lift, the weight of the structures, landing and taxi-bump loads, etc. For certification of an aircraft structure, one might examine tens of thousands of loading conditions, several hundred of which may be critical for some structural element.

The definition of strength requirements for commercial aircraft is specified in Federal Aviation Regulations (FAR), Part 25. Many of the load requirements are defined in terms of the *load factor*, n. This is defined as the effective transversal acceleration of the airplane in units of g, $n \approx L/W$ when angles of attack and sideslip are small.

Flight Envelope

The flight envelope is usually depicted in altitude (H) – Mach (M) (or Placard) diagrams and $V - n$ diagrams with speed V and load factor n (Figure 1.5). Speeds are given as *equivalent airspeed* (EAS): the speed at sea level that would give the same dynamic pressure as the true airspeed (TAS) at altitude.

$$EAS = TAS\sqrt{\rho(H)/\rho(0)} \tag{1.2}$$

The diagrams below are taken from the design of the TCR discussed in Section 1.1.5.

Mach-Altitude Envelope

The top of Figure 1.5 shows a Placard diagram. The left boundary is the low-speed stall limit, set by weight, wing area, and $C_{L,max}$ for the configuration. The right boundary is set by the maximum allowable dynamic pressure and is of the form $M^2 < const./p(H)$, with pressure $p(H)$ taken from the standard atmosphere. The dashed circle surrounding the design cruise condition – the black dot – indicates the necessary region where a stable "healthy" flow pattern must obtain and becomes part of the design strategy.