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.

---

[1] https://doi.org/10.17226/10566, with permission of The National Academies Press.

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.

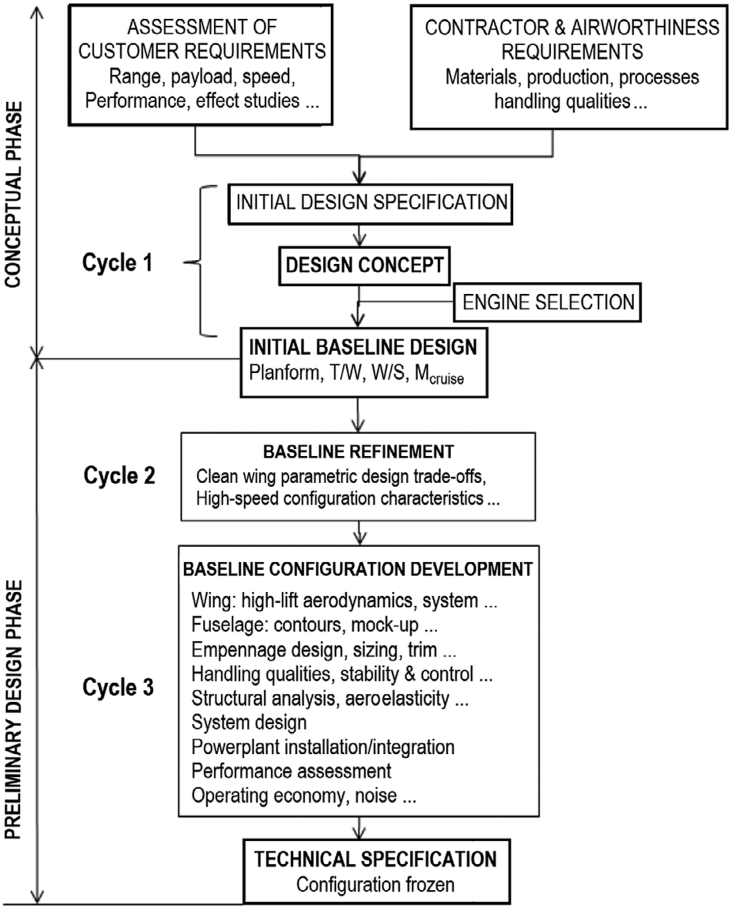


Figure 1.1 Configuration design and development of a typical transport aircraft evolving after a succession of Cycles 1, 2, and 3. (Adapted from Torenbeek [29], reprinted with permission)

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.

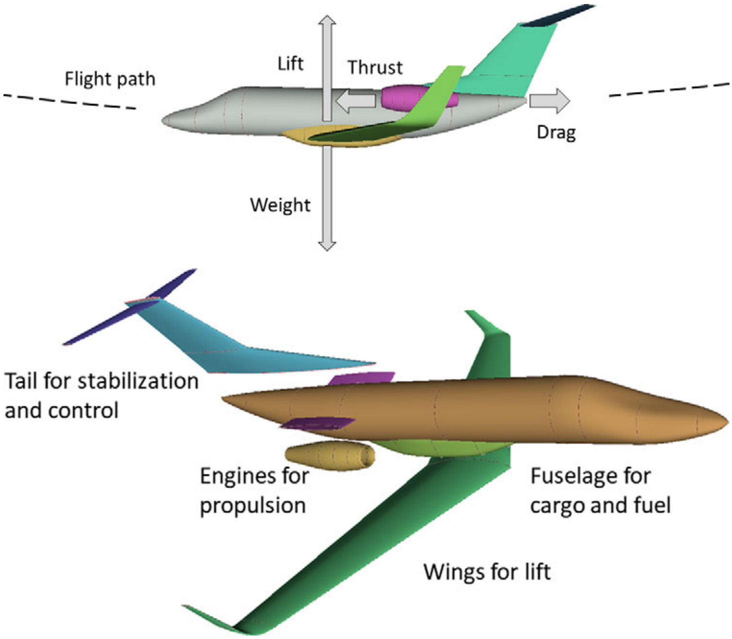


Figure 1.2 Forces in un-accelerated flight and aircraft components. (Top) Lift balances weight and thrust balances drag. (Bottom) Cayley's principle: each component of the aircraft has its distinct function.

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,

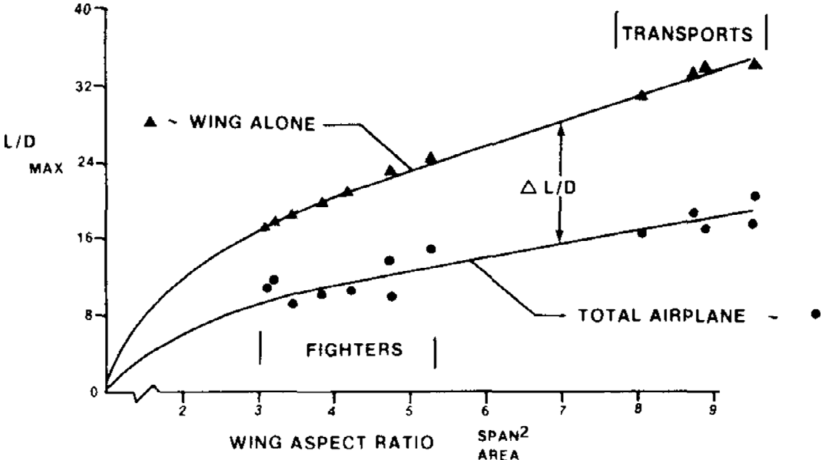


Figure 1.3 Maximum lift-to-drag ratio for total configuration and wing alone vs wing aspect ratio. (From Chuprun [3], AFWAL, public domain)

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

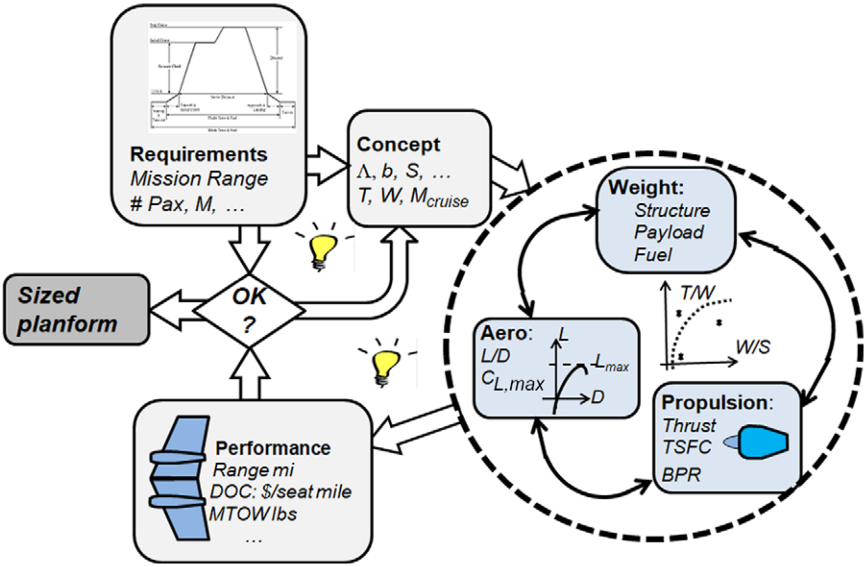


Figure 1.4 Initial sizing process in the Cycle 1 aircraft design process, with outcome of wing planform and size, showing the role of aerodynamics.

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

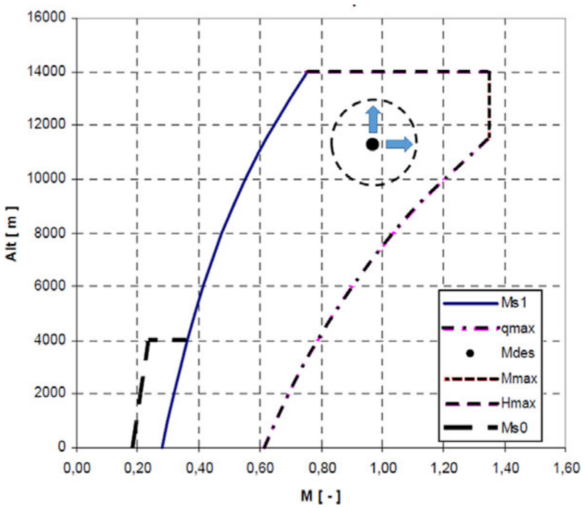
The flight envelope is usually depicted in altitude (H) – Mach (M) (or Placard) diagrams and $V - n$ diagrams with speed V and load factor n (Figure 1.5). Speeds are given as *equivalent airspeed* (EAS): the speed at sea level that would give the same dynamic pressure as the true airspeed (TAS) at altitude.

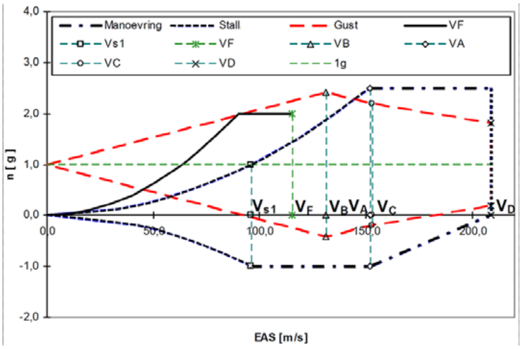
$$EAS = TAS\sqrt{\rho(H)/\rho(0)} \tag{1.2}$$

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.





	Name	Speed [m/s]
V_{S1}	1-g stall speed	96
V_F	Max flap speed	115
V_A	Manoeuvring speed	152
V_B	Speed for max gust	131
V_C	Cruise speed	153
V_D	Dive speed	209

Figure 1.5 Diagrams describing the aircraft flight-state envelope, with a dashed circle indicating the region of stable "healthy" flow surrounding the design point. Top: Mach-altitude envelope; bottom-left: $V - n$ diagram; bottom-right: speed definitions table. (Courtesy of R. Larsson, private communication, from EU project SimSAC [20])

Speeds

Details of how speeds are determined are too technical for this textbook (see the table in Figure 1.5). The $1g$ stall speed V_{S1}, for instance, is the minimum airspeed for level flight (i.e. with load factor 1). It is determined by the maximal lift obtainable and weight.

$$V_{S1} = \sqrt{\frac{2W}{\rho(0)C_{L,max} \cdot S}}$$

Cruise speed V_c is a performance requirement, and dive speed V_D is determined from the q_{max} boundary in the Mach-altitude envelope: $V_D \approx 0.61 \cdot 340 = 207$ m/s.

The maneuvering speed V_a is the maximal speed for maximal control surface deployment: larger deflections could result in load factors exceeding the maximum allowed.

Maneuver Diagram

This $V - n$ diagram illustrates the variation in load factor with EAS for maneuvers. At low speeds, the maximum load factor is constrained by stall (i.e. the aircraft $C_{L,max}$), with high-lift devices deployed up to speed V_F and retracted up to V_D. At higher speeds, the maneuver load factor may be restricted as specified by FAR Part 25. The maximum maneuver load factor is usually $+2.5$.

The negative value of n is -1.0 at speeds up to V_c, decreasing linearly to 0 at V_D. Maximum elevator deflection at V_A and pitch rates from V_A to V_D must also be considered. Loads associated with vertical gusts are evaluated over the range of speeds. The dashed "Gust" line in Figure 1.5 shows estimated gust loads that are probably encountered no more than once per 100-h flight time at that EAS. The gust speeds employed are the result of measurements and statistical models, hence the "probably." The "buffet boundary" is akin to the boundary for "healthy flow." Its limit is not sharp, since the severity of buffet increases gradually with dynamic pressure and mild buffet is tolerable. Low-speed buffet is caused by flow separation as the aircraft approaches stall and the separated flow becomes unsteady. At higher Mach numbers, high-speed buffet is caused by flow separation from the wings by shock–boundary layer interaction.

The flight envelope is not given a priori, but must develop as the design studies reveal more and more of the aerodynamic and structural properties. Low-speed properties like the stall boundary are related to $C_{L,max}$, as discussed in Chapters 8 and 9. Airworthiness certification imposes other limits, such as the fact that a load factor between -1 and $+2.5$ must be tolerated at all speeds up to V_D. These numbers, which are typical for airliners, depend on the type of aircraft.

Parametric Cycle

At this point, the *parametric cycle* of conceptual design starts, evaluating the initial idea and concepts with *many variants* studied. Past experience along with simplified aerodynamic and structural estimates and statistical databases, which we will refer to as "fidelity level L0 Handbook Methods," then synthesize these characteristics into the first concept, an initial sized configuration, together with preliminary performance levels. Note that range is given, whereas aircraft weight (and thus aircraft physical size) is to be calculated. The initial concept may prove, or cast doubt on, the feasibility of the proposed mission. It may appear too ambitious, requiring an excessively large and expensive aircraft, or the indications are that it can be carried out by an aircraft of acceptable size. Thus, the design process takes another iteration, usually followed by yet more iterations, to arrive at a mission and corresponding design that can be expected to capture the desired market share and give sufficient return on investment.

For example, Figure 1.3 indicates how $(L/D)_{max}$ increases with aspect ratio because induced drag decreases. It would seem that you should design the wing with

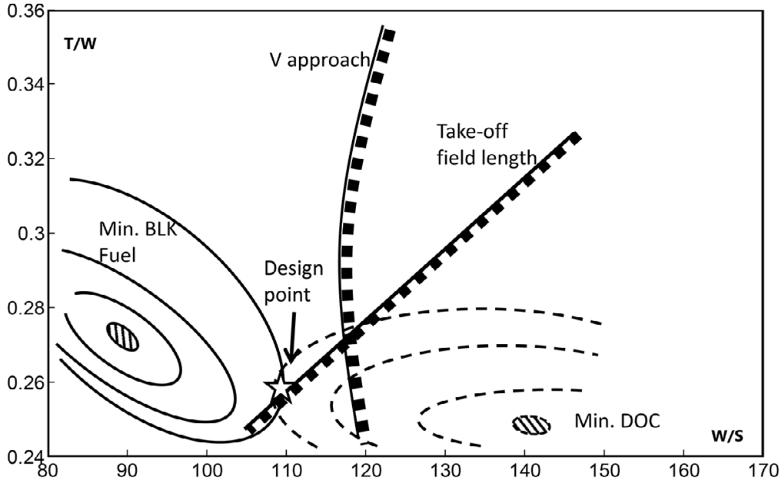


Figure 1.6 Constraints and isocurves of measures of merit in the W/S–T/W diagram.

a very high aspect ratio. However, due to the higher strength required and thus heavier structure, wing weight increases with increasing aspect ratio and area. Since the goal is a wing with the necessary lift and the least weight and drag, trade-offs between the structural and aerodynamic benefits are necessary to find the best compromise.

With the planform described mathematically, the analysis procedures can estimate the concept's functional properties, such as its:

1. Weight and balance, including payload, fuel, systems and structural weight predicted by structural design
2. Thrust and fuel needed to carry out the mission to fly at a specified cruise Mach number
3. Lift and drag forces during the mission

These procedures in turn generate the data to estimate performance and flight dynamics in order to determine whether the concept fulfills the requirements and goals for the design.

Outcome: Sized Baseline Configuration

Once converged, the initial iteration loop yields a *baseline configuration*, a three-view drawing, including the wing planform sized to fulfill the mission and represented by a small number of parameters, given in Table 1.1 and displayed in Figure 0.1. It is common to display a T/W versus W/S diagram such as Figure 1.6 with the various requirements and criteria as boundaries for feasible designs. Usually, the *set* of design parameters **X** is fixed, so the various quantities of interest, such as takeoff field length and direct operating cost (DOC), can be worked out for some given *values* of **X**. Such parametric studies also produce *sensitivities* of performance measures of parameter changes, for small excursions in the design space from the design point (i.e. within the dashed circle in Figure 1.5). The constraints are shown in Figure 1.6 as curves with cross-hatches on the forbidden side. The landing speed limit is almost independent of T/W: the limit on landing speed $V_{approach} < limit$ is determined essentially by wing loading W/S,

$$W/S = L/S \leq 1/2\rho_{air} limit^2 \cdot C_{L,max}, \tag{1.3}$$

since the attainable maximal lift coefficient $C_{L,max}$, defined in Eq. (0.1), is determined by the wing shape and the aerodynamics "laws." Takeoff length is also influenced by the thrust, hence its sloping constraint line.

The block fuel "BLK Fuel" is the amount of fuel necessary to fly the mission, and it depends on weight, speed, drag, and engine efficiency. DOC is measured in, say, dollars per seat mile. The design point must be in the feasible subset allowed by the constraints, most probably on the boundary of it. Now consider the iso-curves for DOC and BLK Fuel, a design point, and moving it in some direction. It is clear that for the point to be good there must be no directions that improve both measures. This is the definition of the Pareto front for the two objectives (see any standard textbook on optimization techniques for an explanation of the Pareto front). So the trade-off is between points on the Pareto front for DOC and BLK Fuel.

We now have at the design point T/W and W/S. For cruise $T = D$ and $W = L$, so

$$\frac{T}{W} = \frac{1}{L/D} \text{ and } \frac{W}{S} = q\, C_L, \tag{1.4}$$

which gives requirements for the wing aerodynamics to fulfill where $q = 1/2\rho(alt)V_\infty^2$ is dynamic pressure, dependent on altitude and airspeed.

Designs Vary Widely

Figure 1.7 indicates how greatly the resulting design can vary depending on mission requirements, from human-powered aircraft at the bottom-left to jet fighters at the top-right. Note that the ordinate is *power*-to-weight, and that the scales are logarithmic to cover the vast expanse of this design space.

Sizing

"Sizing" is the design process that determines the aircraft takeoff gross weight, empty weight, and fuel weight required for the configuration to perform a specified mission with a specified payload weight. This calculated size is used to estimate a revised wing area, fuselage length, etc., appropriate to the determined weight. For a detailed description, see Raymer [19].

Initial sizing determines the specific geometric data needed for the baseline layout by analyzing the aerodynamics, weights, and propulsion characteristics in order to check all performance requirements for the design mission. Decisions and trade-offs are traditionally made on the basis of compilations of carpet plots of the parameter

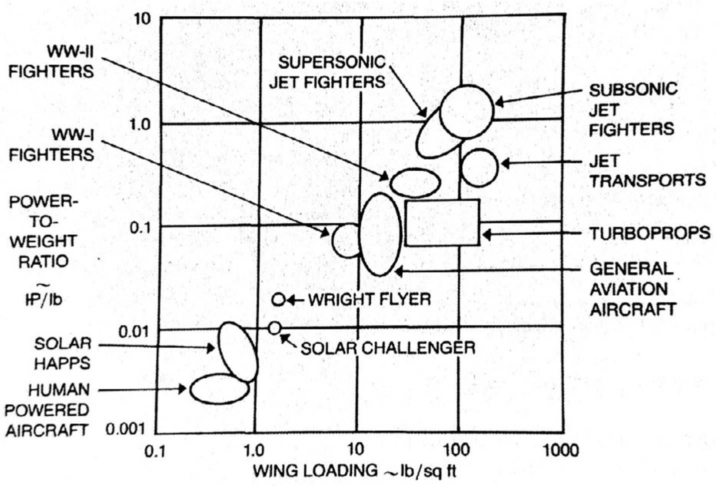


Figure 1.7 Mapping of aircraft classes onto the thrust–weight landscape. (Courtesy of David Hall [11])

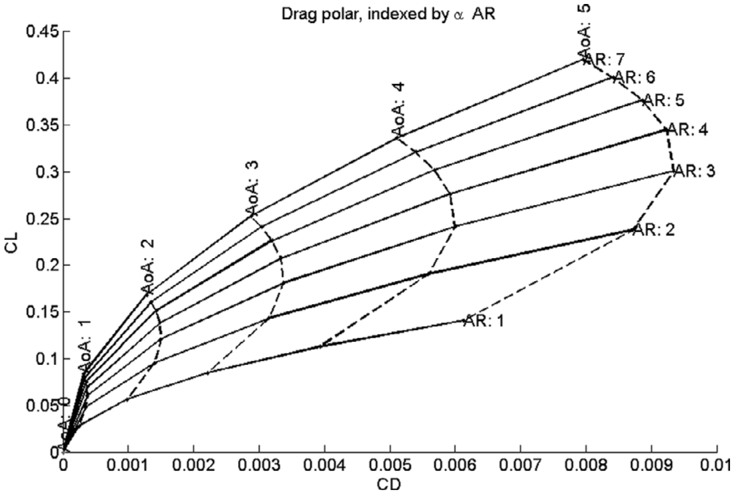


Figure 1.8 Carpet plot: $C_L, C_D, \alpha = AoA$, and AR.

studies: a carpet plot shows graphs of four variables constrained by two relations. Figure 1.8 is an example of this, showing lift and induced drag coefficients, angle of attack α, and aspect ratio AR for rectangular wings at low speed.

Creativity

The design process just summarized involves much *creativity*, as symbolized by the light bulb symbol below, and it is not easily taught, as is explained in the panel below.

Panel: Creativity – when the *light bulb* glows

The “light bulb” symbol is used in our figures to indicate creativity – an important part of the design process.

Creativity is not in the realm of technology; rather, it belongs to the cognitive aspects of the human brain. How we create is assessed in neuroscientific studies, which indicate that human beings innovate by absorbing the best *existing ideas* and making them *better*. “Whether inventing an iPhone, manufacturing the next-gen aircraft, or launching modern art, creators remodel what they inherit,” write the authors Brandt and Eagleman in their book *The Runaway Species*. We do so by engaging in three basic strategies by which all ideas evolve: “bending, breaking, and blending.” We take the raw materials of experience and then bend, break, and blend them to spawn outbursts of creative activity symbolized by a bulb lighting up, leading to new outcomes. Unlike wild creatures, who operate largely on autopilot, humans usually avoid repetition and seek novelty, whence the dictum *think outside of the box*. Brandt and Eagleman’s narrative is filled with tips on how to produce successful ideas: practice, experiment, generate many ideas, and let most die. A cornerstone of the creative process is to generate *options*, which is equally applicable to aerodynamic design, as in Hemingway’s reputed 39 endings to *A Farewell to Arms*.

Handbook Methods to Size the Baseline Configuration

The design and analysis methods discussed in the book assume that a sized baseline proposal exists. This begs the question of *how* to produce a sized baseline if we do not have the design tools for all disciplines shown in Figure 1.4.

Handbook methods capable of producing sizing information on weights, wing planform, and propulsion from basic mission requirements are presented in aircraft design textbooks and their accompanying software. They belong to fidelity level L0. Raymer’s classic textbook on conceptual design [19] is an excellent starting point, complemented by its RDS software package. In addition, Roskam’s book [23] and associated commercial AAA software from the DAR corporation is recommended.

The USAF Data Compendium (DATCOM) [13] is a collection of algorithms, formulas, and design rules based on physics, statistics from data for many existing aircraft, and curve fits, obtained through the Air Force’s long-standing cooperation with aerospace companies. The Digital DATCOM software [30] is capable of producing weights, inertias, and force and moment data from subsonic to supersonic speeds from the DATCOM formulas and algorithms and scant geometric information on the configuration. Its fidelity is limited to (and for) conventional configurations.

ESDU (www.esdu.com) is a high-end commercial product providing validated engineering analysis tools for aerospace engineering. The tools include methodologies, design guides, equations, and software.

With some experience of and access to such L0 tools, the design team will look for useful templates from, for example:

1. Raymer's webpage (www.aircraftdesign.org)
2. the SUMO aerospace CAD package [14]
3. European collaborative projects such as
    SimSAC [20, 22]
    AGILE [4], and its Academy [6], etc.

Then the work begins, as the next section exemplifies.

1.1.5 Example: Sized Baseline Configuration – The TransCruiser

High-Speed Civil Transport and the Saab TransCruiser

The US High-Speed Research program was started in 1990 aiming at Mach 2 transoceanic flight. The High-Speed Civilian Transport concept presented in 1995 had a "cranked" wing. Its inner part was highly swept, with a leading edge extending far forward along the fuselage, and the outboard panel was less swept. The cranked wing concept is similar to the F16-XL research aircraft built for high-speed research as a stretch of the standard F16 (Figure 1.9). The wing modification aimed at improved supersonic and preserved transonic performance. The F16-XL was instrumented to provide a wealth of flight data, including pressure maps through the transonic speed range. The availability of the data for a wing similar to the HSCT concept provided a unique opportunity for CFD correlation and code validation with flight and wind tunnel data.

The HSCT project was abandoned due to economic and environmental issues, such as sonic boom concerns. In 2001, Boeing announced the Sonic Cruiser concept, also

Figure 1.9 The F16-XL in flight. (From Elegance in Flight [18], NASA, public domain)

with a cranked wing. With a range of 10,000 nautical miles and a cruise Mach number above 0.95, it was thought to be a competitive configuration. Its cranked leading-edge allowed leading edge high-lift devices, so take-off and landing would not require extreme angles of attack. The Concorde, with its curved leading edge, had no slats, needed a high angle of attack at take-off and landing, and resorted to drooping the nose for better pilot vision.

Hepperle [12] carried out a concept study on a possible aircraft configuration. One result of the study is that, due to the near-sonic speed and high drag, the concept encounters demanding engineering challenges within a very narrow design space. John F. Kennedy’s “We choose to go to the moon” address comes to mind:

> We choose to …do the other things, not because they are easy, but because they are hard.

Similar to the Boeing Sonic Cruiser, Saab proposed the cranked wing TransCruiser (TCR), cruising at Mach 0.97, for one of the Design, Simulate, and Evaluate exercises in the SimSAC Project [20–22]. Cycle 1 work starts with the development of an initial baseline design, using L0 in-house sizing methods. It is inefficient to fly very close to the sonic wall, such as Mach 0.97. Saab purposely selected this case to *stress* the shortcomings of their in-house methods for predicting characteristics in transonic flight.

Specification and Baseline Configuration

Table 1.2 spells out the requirements for the TCR design.

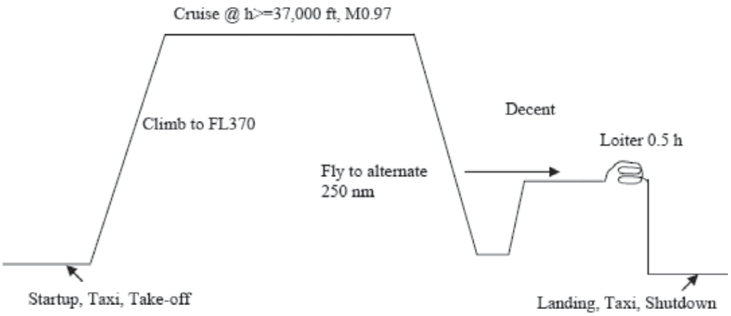
Using in-house design methods, the Saab team produced the sized baseline configuration in Figure 1.10. The sizing procedure includes many aspects, among them estimates of weights, engine performance, and aerodynamics. The landing and cruise phases define constraints for thrust-to-weight and wing loading. The predicted aircraft weight is also an output of the procedure. The outcome from this sizing is as follows.

- Maximum take-off weight (W_0): 227 metric tons × g = 2,225 kN
- Required static thrust (T_0): 890 kN
- Required net wing area (S_{net}): 377 m^2

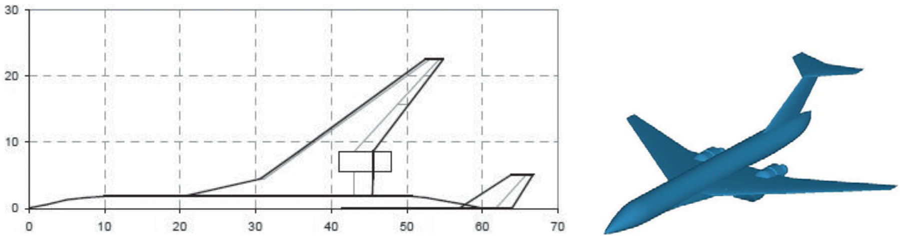
The design C_L varies from 0.48 at Mach 0.8 to 0.3 at Mach 0.97

Table 1.2 Nominal TCR specification.

Parameter	Requirement
MTOW	180 metric tons × g = 1766 kN
No. Pax	200
Range	10,000 km (5500 nm)
Design cruise speed	$M_c = 0.97$
Baggage and freight	LD3-46W containers



(a) Mission profile of the TransCruiser.



(b) Top view of configuration

(c) CAD representation of baseline configuration

Figure 1.10 The baseline T-tail configuration for the TCR exercise. (From EU project SimSAC [20, 21], courtesy of Roger Larsson)

The baseline is a 'mid-to-low'-winged T-tail configuration with two wing-mounted engines. Ailerons and rudder are used together with an all-moving horizontal tail for control. Flaps and slats are used as high-lift devices. The landing gear is a conventional tri-cycle type with main gears mounted in the wing (see Figure 1.10).

The Saab team concluded their Cycle 1 design with the following conclusions and suggestions:

> Classical flight-mechanics analysis indicates that the base-line is stable in pitch at all time, and increasingly so in the transonic region, but the elevator effectiveness is low. The TCR aircraft is both laterally and directionally stable throughout the whole Mach envelope. The flying characteristics are generally good, and the control system can easily improve the undesirable Short period and Phugoid-mode characteristics. The main problem with the baseline is the excessive elevator angles needed for trim. The elevator angle should be not more than 5 to 10 ° for most flight conditions, we estimate it to be nearer to 15 °. It follows that the elevator effectiveness together with the pitch stability, especially in the transonic region, should be improved in Cycle 2. An option is to re-position the main wing and modify the horizontal tail layout.

For the purposes of this book, the TCR transonic cruiser has all the ingredients to make an excellent case study for using the aerodynamic tools to take the initial aircraft specification through Cycle 2 to a feasible concept, and then through Cycle 3 for closed-loop control system design in the following steps. Chapter 1 presents the baseline TCR configuration.

A votex lattice method (VLM) model (L1) is created by the tools of Chapter 3.

Chapter 5 produces a CAD model and grid for L2 analysis.

Chapter 8 studies the airfoil used to shape the wing.

Chapter 9 describes the aerodynamic redesign from variants TCR-1 to TCR-4 to TCR-C15.

Chapter 10 covers the iterative process that solved the trim problem, presents the prediction of flying qualities, and draws overall conclusions.

1.2 Advanced Wing Design: Cycle 2

The baseline sizing procedure, Cycle 1, is a broad-ranging exploration over the parameter space embracing much cross-disciplinary-type analysis ranging from aerodynamics through manufacturing and costs. The work is usually carried out in the Future Projects Office of the aerospace company. A complete layout consists of the baseline design showing three view drawings and some principal cross-sections.

If the concept is to be developed further, the next step is to check the extent to which the characteristics and performance of the design will meet the design requirements.

The Future Projects Office hands this work over to the Advanced Design Office, where further development (Cycle 2) begins with experts in each respective discipline (e.g. aerodynamics) to establish the technically consistent feasibility of the design. Figure 1.1 indicates this “hand-off” of the “Initial Baseline Design” to the “Advanced Design” teams to further explore the parameter space. The object is twofold: first, to improve the design where it does not meet the requirements; and second, to investigate the most likely possibilities and to determine whether other variants may prove a better proposal. A protracted and labor-intensive effort involving more advanced trade studies develops the baseline in greater detail to become a realistic candidate. A family of designs thus emerges that are easily comparable with each other as well as with the baseline design.

Although the fidelity of the methods used should be as high as possible, there always remains uncertainty. It is necessary to carry out further detailed investigations in Cycle 3 of (at least) *two* alternative configurations to differentiate between the evolving designs before an irrevocable choice is made.

Design Examples

Chapter 9 presents a number of historical examples beginning in the 1940s with a study of one of the first swept-wing jet fighters, the Saab J 29. The Mach 2 Concorde was designed in the 1960s when CFD was incapable of producing flow solutions across the speed range. Its design uses purposely separated vortical flow over the highly swept delta wing to give reasonable lift at low speed. The 1970s saw Saab developing the SF340 commuter turboprop with modern NASA airfoils. The Common

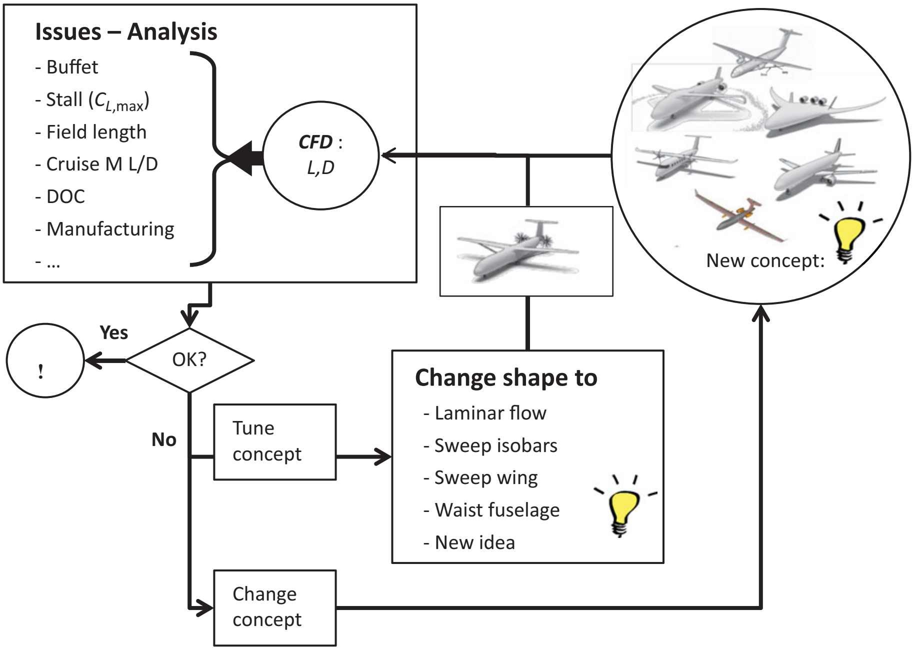


Figure 1.11 The design loop, Cycle 2, intersperses tuning of the selected concept with changing focus onto another – perhaps only just invented – concept.

Research Model is a configuration study that is typical of transonic airliners today, with details of shape published to encourage further optimization studies using CFD.

Tasks and Tools

This section goes further in identifying more precisely the aerodynamic tasks to improve the baseline performance, as exemplified by Figure 1.11. In a quantitative way, it spells out the protocol for the design parameters, shape variables, and performance measures.

Low-fidelity tools are traditionally used by the Future Projects Office in the concept design Cycle 1, where many alternatives need to be analyzed in a short period. Higher-fidelity tools are used by the Advanced Design Office in the following Cycles 2 and 3 as the multiple concepts narrow down to a few that are mature enough for such tools. The term “mature” refers here to the representation of the aircraft’s outer-skin geometry and its internal structure, where applicable. This in turn influences the fidelity of the aerodynamical modeling that determines the aircraft’s behavior and performance. Today, this is the existing practice for developing new aircraft.

We focus on the CFD-related tasks in Baseline Refinement. Clean-wing design is treated in Chapters 8 and 9 and must produce a light wing with high lift-to-drag in cruise and good low-speed properties. The secondary parameters for detailed aerodynamic wing-shape design are shown in Table 1.3. This sets the stage for refinement of

Table 1.3 Secondary parameters for clean-wing design.

Section shape	Parameter
	Thickness chordwise Camber line chordwise Leading-edge radius R_n Trailing-edge angle τ_{te}
Spanwise shape	**Parameter**
	Twist variation spanwise Camber variation spanwise $(t/c)_{max}$ variation spanwise

the whole configuration through analysis of the flying qualities. Chapter 10 covers the sizing of control surfaces, rudders, elevators, elevons, canard, spoilers, and ailerons, if they are present. Compilation of the tables of the aerodynamic forces over the flight envelope, which is necessary for flight simulation, is discussed. Finally, Chapter 11 presents a low-fidelity model for investigating the effects of the deformations of the airframe in flight and maneuvers.

1.2.1 Aerodynamic Wing-Shape Design

All airplanes must perform satisfactorily over a range of speeds. Look at Figure 1.5 and Figure 1.11. To achieve acceptable operation across the flight envelope, airplanes must adapt the geometry of their lifting surfaces to different operation points. A transport airplane could be said to have three main design points in the flight state envelope: take-off and climb-out, cruise, and landing. In the first condition, the flaps are set for take-off conditions (i.e. at not too large angles to ensure low drag). The wing is designed for cruise with the flaps retracted. In landing, drag is beneficial and the flaps are set at large angles to increase lift and reduce landing speed. For each of these flight conditions, effects of deviations in speed and attitude as well as of gusts must be considered. The aerodynamic design must give the airplane a well-ordered, stable flow in all of these conditions.

Clean-Wing design

Clean-Wing design is one of the cornerstones of aircraft manufacture, and details of the procedures used are well-guarded intellectual properties of the manufacturers. It is safe to assume that creation of an efficient wing from scratch for a new configuration requires significant industrial effort and one or more years of devoted time. Ryle [24] gives us a detailed account of wing design in the 1970s, but leaves out much of the relevant mathematics. Obert's book [17] also describes the process.

At the time of Ryle's writing, CFD was in its infancy, and accurate computation from first principles of the transonic flow around a suggested wing was all but impossible. Thus, experimental data provided the main guidance, together with potential flow as the workhorse mathematical model (Chapter 3), corrected in various ways such as the Prandtl–Glauert Mach number scaling for compressibility effects and shape modification by estimated boundary-layer displacement thickness.

It is also safe to assume that there is much to gain by copying an existing wing that is known to be efficient and modifying it to satisfy the new performance requirements. Wing design for unconventional configurations is an even greater challenge, since there is no obvious baseline to start from.

Conceptual design is a very repetitive process, with the design evolving with each iteration. New ideas come forth in response to problems as they are uncovered when the design is investigated in ever-increasing detail, as illustrated in Figure 1.11, which highlights aerodynamics. Similar analysis/synthesis loops appear for the design of the structures, the propulsion, the control system, etc. The analysis step is structured with quantitative tools to put numbers on the features and properties once a shape has been defined. The shape change to achieve the desired effect may be a small nudge along well-known directions. But when the well-known ideas have been exhausted, a creative step is called for. We maintain that such *creativity* is best learned on the job, by trying and sometimes failing, and by studying the masters. But software can help unfetter creativity in the engineering teams. It can take care of menial tasks such as file formatting and running computational tools in “workflows” involving several computational analyses over and again. Computers do this without the errors typical of humans in repetitive jobs with many details to get correct. They can also, without fail, log all analysis steps for backtracking and documentation.

Real Wing Design and Optimization

The shape of a real wing must also satisfy non-flow-related geometric and structural constraints. The wing must have sufficient volume to contain the fuel and control surface actuators, be thick enough to carry a wing box that can withstand the aerodynamic loads, and be simple enough to allow economic manufacture. Aero-elastic effects must also be taken into account. The designer must *create a shape* with low drag at cruise, safe stall characteristics, and satisfactory divergence, flutter, and buffet speeds.

This is much more complicated than choosing the shape from a given family that minimizes the drag at a given lift coefficient and Mach number by running an optimization algorithm. It is reasonable to ask what help solutions of such simple tasks can be to the design office. There is, of course, the long-term hope that, with *much* faster computation, the complexity of the optimization task can be increased to become more realistic, and that the algorithms will become less myopic in their search of the design space.

But in the near term, optimization exercises are already very useful in at least two different ways. First, they show *patterns* of shape modification and the resulting flow changes, so that the engineers learn more about the mapping from *shape to performance*. Second, they are useful in shape modifications to shave the last drag counts off an already well-designed wing by weakening shocks or reducing adverse pressure gradients locally. It follows from these deliberations that software tools for aerodynamic design should provide efficient solutions to tasks formulated as optimization problems where the objectives as well as constraints can be easily changed.

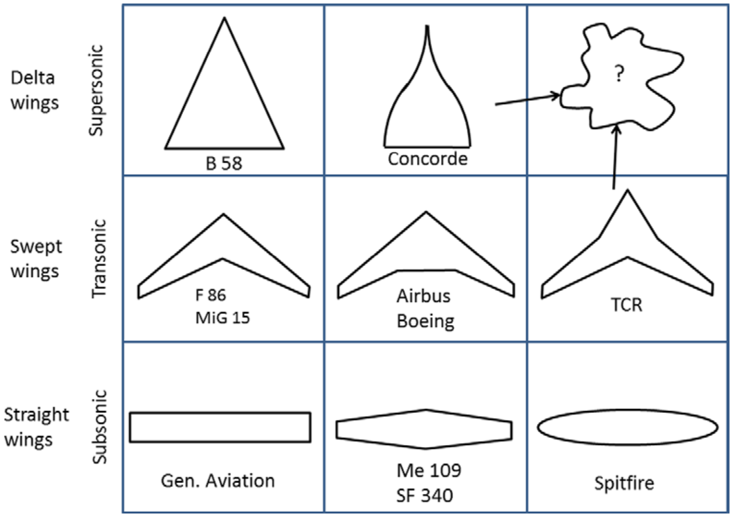


Figure 1.12 Variations of the three planform classes. Straight wings (bottom) for subsonic flight; swept wings (middle) for transonics; and delta or arrow wings (top) for supersonic speeds.

In the following, we consider only the aerodynamic shape optimization subtask in the *decomposed overall design task*, epitomized in Figure 1.11.

Aircraft conceptual design processes can be improved by proper application of multidisciplinary optimization (MDO). MDO techniques can reduce the weight and cost of an aircraft design concept by making fairly minor changes to the key design variables, and with no additional downstream costs. In effect, we can get a better airplane for next to nothing. An overview is presented in Section 1.3.1.

Speed Regimes and Planforms

Figure 1.12 shows several variants of the basic three planforms: straight, swept, and delta. The main wing planform variants for high speed are the swept wing (backward and forward), the swept wing with strake, the delta wing, the delta wing with canard, and the hybrid wing. The hybrid wing is a trapezoidal wing combined with a strake, also called a leading-edge extension (LEX). The trapezoidal wing typically has a well-rounded leading edge with rather small sweep angle, $\Lambda_{LE} = 25$–$45°$. The strake is a slender, far forward-reaching, highly swept inner wing with a small leading-edge radius. The leading edge may be straight or slightly curved. The cruise speed increases, as does the sweep angle, from subsonic straight wings in the bottom row of Figure 1.12 to transonic swept ones in the middle row, and then to supersonic with highly swept wings in the top row. The determining factor is the Mach number, M_{cruise}, the ratio of airspeed to the speed of sound. Supersonic craft all are slender, with small wingspan-to-fuselage length ratios. Many more variations have evolved from the three basic ones. The US fighters have hybrid small aspect ratio swept wings with various LEXs. In the EU, the later generations of manned fighters instead have delta

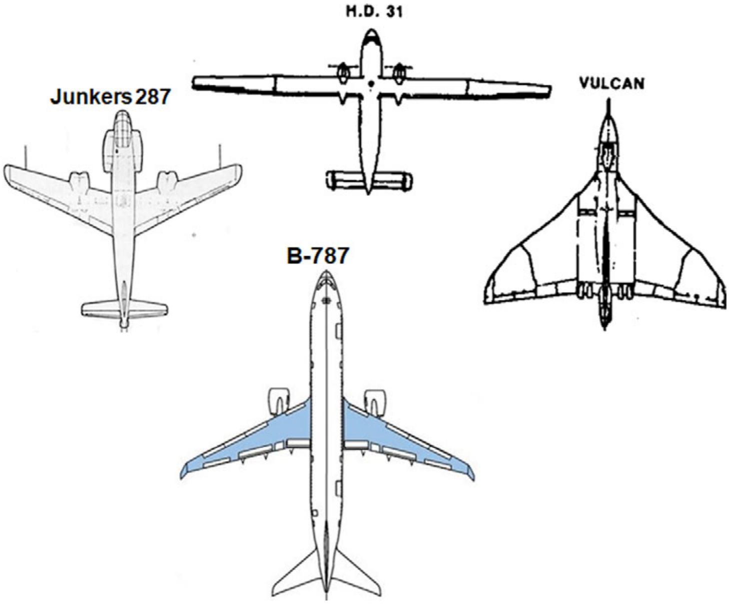


Figure 1.13 Four different planforms. (Top) The very high aspect ratio Hurel–Dubois HD.31. (Center left) The Ju 287 jet World War II bomber with forward sweep. (Center right) The delta wing Avro Vulcan strategic bomber. (Bottom) The Boeing 787 Dreamliner, a typical modern long-range airliner. (Adapted from Chuprun [3], AFWAL, public domain)

(or double-delta) wings with canards. Unconventional configurations such as flying wings and Prandtl box wings evolved as combinations of these elements. For instance, winglets of many different shapes now appear on modern planes designed for low cruise drag. More detailed discussions on transonic and supersonic planforms can be found in Chapters 3 and 9.

Examples: Advanced Design Work

Reflecting the wide variety of aspect ratios and sweep angles in Figure 1.12, Figure 1.13 shows four very different wing planforms that have found their way onto flying aircraft. One is a classical wing with extreme aspect ratio, and the other three are different solutions to the challenge of high-speed flight. It would seem that the high aspect ratio swept wing is the current best practice for economical close-to-Mach-1 flight.

The Junkers Ju 287 was a German World War II aerodynamic test bed built to develop the technology required for a multi-engine jet bomber. It was powered by four Junkers Jumo 004 engines and featured a revolutionary forward-swept wing. Later prototypes were captured by the Red Army in the closing stages of World War II and the design was further developed in the Soviet Union after the end of the war. Flight tests displayed extremely good handling characteristics, but also revealed some of the problems of the forward-swept wing. The most notable of these drawbacks was "wing warping," or excessive in-flight flexing of the main spar and wing assembly. Forward sweep makes the wing tip twist up, increasing the lift on the outer part, which further increases the twist. Swept-back wings are free of this vicious cycle, but, as we shall see later, they have other problems.

The Hurel–Dubois HD.31 was produced in France in the 1950s, based on Maurice Hurel's high aspect ratio wing designs. Tests with the Hurel–Dubois HD.10 research aircraft had validated Hurel's ideas. Two prototypes of a medium-range airliner utilizing this principle were built, conventional designs in all respects other than their unorthodox wings with an aspect ratio of 20.2!

The Avro Vulcan, later named the Hawker Siddeley Vulcan, a jet-powered delta-wing high-altitude strategic bomber, represents a highly successful "Flying Wing" type with compound leading-edge sweep. Several scale aircraft, designated Avro 707, were produced to test and refine the delta-wing design principles. Influential in the design was wind tunnel testing performed by the Royal Aircraft Establishment at Farnborough. This indicated the need for a wing redesign with breaks in the leading-edge sweep to avoid the onset of compressibility drag, which would have restricted the maximum speed.

Representing a current airliner, the Boeing 787 Dreamliner first flew in 2009, with high aspect ratio wings and winglets. It is built with carbon fiber composites. The chevrons on the nacelles reduce nozzle exhaust noise by influencing the mixing layers between the high-speed core and bypass flows and the exterior flow.

1.2.2 Aerodynamic Cruise Efficiency and Wing Planform

Thus, the task of aerodynamic design becomes that of *aerodynamic shape optimization*, and just as in Figure 1.13, the planform can vary greatly to achieve optimum aerodynamic cruise efficiency. Figure 1.14 illustrates the three "sweet spots" for speeds of the DC-3 at the low end, the Concorde at the high end, and a typical transonic jet airliner in-between. As we shall investigate in Chapter 9, the TCR cruises inefficiently just below Mach 1. The parameter most often used to assess the aerodynamic cruise efficiency E of a transport configuration is the product of the cruise lift-to-drag ratio, L/D, and the cruise Mach number, $\mathsf{E} = M(L/D)$. This parameter is directly related to the range of an airplane (Eq. (1.3)).

Critical Flow and Transonic Drag Rise

For a "classical" type of aircraft, L/D is approximately constant until the *critical* Mach number M_{crit} of the wing section, the flight Mach number at which supersonic flow first appears, is reached.

At higher speed, drag increases significantly due to compressibility effects: local pockets of supersonic flow terminated by shocks produce wave drag- and/or shock-induced separation. Therefore, E will vary approximately linearly with Mach number until M_{crit} is reached, and then decrease quite suddenly because the drag increases rapidly above M_{crit}. The slope of the E curve increases with wingspan as described by

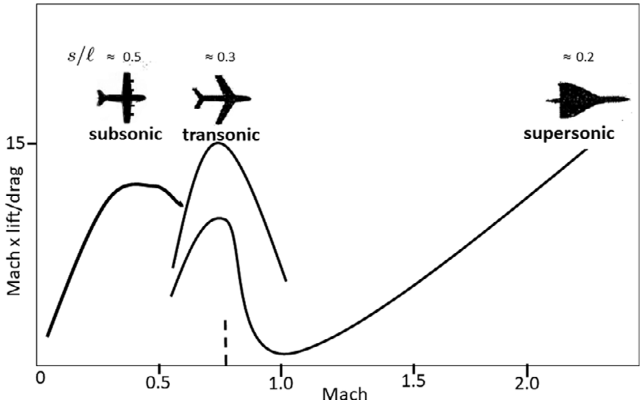


Figure 1.14 Wing cruise efficiency for three classes of aircraft in three different speed regimes.

wingspan load efficiency e (see Eq. (1.5)) and decreases with increased wetted area of the configuration.

The airfoil technology sets M_{crit}, and it decreases when the lift coefficient or the wing thickness increases. Improvement in airfoil technology typically produces a slight change in the slope of the E curve and a continuation of the straight portion to higher M_{crit}. The gain in E with advanced airfoil technology is then proportional to the increase in the critical Mach number.

A few relationships clearly and simply reveal the way in which the several measures of airplane characteristics affect airplane performance. The lift-induced drag of an airplane typically varies parabolically with lift C_L,

$$C_D = C_{D,0} + k'C_L^2/(\pi AR) = C_{D,0} + C_L^2/(e\pi AR), \tag{1.5}$$

a relation predicted by, for example, lifting line theory (Chapter 3). Another general relation is the specific range equation (Eq. (1.1)). The basic credo is that *the most economic aircraft travels farthest per gallon of fuel burned.* The TSFC appearing in the specific range is approximately a constant for jet propulsion,

$$dW/dt = TSFC \cdot T \text{ Jet propulsion,}$$

but for propeller propulsion with a piston engine, fuel consumption is proportional to the power, VT,

$$dW/dt = PSFC \cdot VT \text{ Propeller propulsion.}$$

From this, Smith [26] derives a relation for propeller aircraft showing that $(L/D)_{max}$ varies with $AR^{1/2}$, hence gains from increased aspect ratio are fairly substantial. $(L/D)_{max}$ improves as $C_D^{-1/2}$, so reductions in friction drag help greatly. For the jet airplane, the effects of these parameters are somewhat different. Now the gains from the aspect ratio vary only as $AR^{1/4}$, while the gains from drag reduction vary as $C_D^{-3/2}$. Thus, compared with piston-propeller airplanes, the jet will tend to have a lower aspect ratio, and its aerodynamic cleanliness, above all low-wave drag, must be at a premium.

What Supersonic Cruise Speed? Concorde Example

During the initial planning of the Concorde design concept (the speculative Cycle 1) in the 1960s, the prospects for favorable L/D ratios at supersonic speed were not promising, owing to the shock-wave drag and the tendency for the lift coefficient to fall with Mach number. There was thought to be a chance of achieving shock-free flows up to Mach 1.2 by increasing sweep, carefully shaping the body/engine-pod junctions and wingtips, and using judicious twist and camber.

Thus, fairly straightforward extensions of contemporary Mach 0.8 swept-wing transports might offer cruising at 50% higher speed. However, it proved difficult to evolve shapes that gave sufficiently high L/D to counterbalance the adverse effects on economy at low supersonic speed and low engine efficiency.

The speed range Mach 1.8–3.0 looked more attractive. The fact that supersonic L/D ratios, albeit low, did not worsen with Mach number meant that the speed should be as high as possible. Long, *slender shapes* could produce good aerodynamics. When combined with confident predictions of greater engine efficiency, the higher speed gave acceptable productivity and encouraging cost figures.

At the lower end of the speed range, it was thought possible to evolve shapes that also had reasonable landing performance. The optimum appeared to lie between Mach 2.0 and 2.5, and the choice within this band rested as much on structural and powerplant considerations as on aerodynamics, since kinetic heating difficulties mount very rapidly. While L/D is not much different from 7.5, being roughly half as good as a transonic airliner, the doubled M compensates in terms of cruise efficiency. In addition, the greater intake compression improves the engine efficiency, which could mean greater range or more payload. Chapter 9 examines further the aerodynamic design of Concorde carried out in Cycle 2.

1.2.3 Why the Slender Delta?

The designers faced a number of concerns in their initial configuration studies. Compared with skin friction and vortex drag due to lift, the major obstacle to economic supersonic flight is the large wave drag associated with lift and volume. Ever since supersonic flight was first seriously considered, it was understood that wave drag could be kept low by using slender shapes. Elongating the fuselage was the obvious line to take, but elongation of the wing required much more careful consideration.

As explained in Chapter 3, it makes sense to keep the wing's leading edge behind the Mach lines, and certainly to keep the whole aircraft well within the Mach cone from its nose, simultaneously distributing the volume and lift fairly evenly.

During the development of aircraft for high-speed flight after the World War II, sweepback steadily increased and thickness and aspect ratios decreased, tending toward the delta planform. Supersonic aircraft demanded even thinner wings and more elongated fuselages, so greater extremes of aspect ratio and planform began to be explored. It appeared that, due to their small wave drag, long, slender aerodynamic shapes, advocated by Dietrich Küchemann at the Royal Aircraft Establishment (RAE), promised to be serious contenders in generating an L/D enabling economic cruising at Mach 2. In addition to thickness ratio, the other geometric parameter that greatly influences supersonic drag is the *slenderness ratio* s/ℓ, the ratio of semi-span s to total length ℓ of the aerodynamic shape. For a lift coefficient of 0.1 at Mach 2, the drag is at a minimum when $s/\ell = 0.2$. This helps explain why slender delta planforms looked attractive, although, at the time, the possibility of landing them satisfactorily seemed rather remote.

1.3 Integrated Aircraft Design and MDO

For more than 50 years, conceptual aircraft design has involved parametric studies by the traditional carpet plot technique that poses trade-offs among sets of four variables constrained by two relations. The perspective on the design process is widened here to include additional discussion of optimization.

1.3.1 Protocol for Aircraft Design Optimization

Conceptual design is primarily a search process. Its goal is to find a set of design variable quantities $\mathbf{X}$, which produces a vehicle that fulfills some desired list of minimum requirements (see Figure 1.15).

The mechanism behind this search is mathematics, and the core utilities required to conduct the design process can be itemized as follows, starting with the design

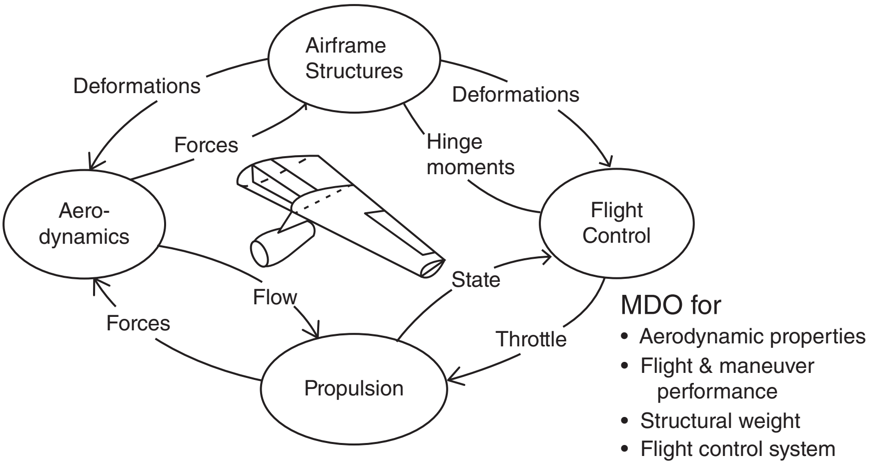


Figure 1.15 Integrated MDO design, Cycle 3, where subfields such as flight control, propulsion, aerodynamics and airframe structures are weakly coupled to each other through constraints imposed by the coupling.

specifications or requirements **R** that define the success of any aircraft design candidate. If a requirement is strict, it is incorporated into the set of constraints; if it can be relaxed, it may be incorporated into the figure of merit (FoM).

- The design parameters **X**, a set of abscissa values intentionally selected to define the airplane in a physically tangible sense, describing the vehicle's physical features or characteristics. The dimension of the *design space* is the number of parameters, which can run to tens of thousands.
- **P**, a set of vehicle properties that satisfy functional relationships, say $\mathbf{P} = prop(\mathbf{X})$, with the design parameters through physical principles or statistical correlations, with fidelity levels L0–L3.

  Examples are the flow prediction methods, such as VLM, to be discussed in Chapter 3.
- $\mathbf{FoM} = fom(\mathbf{X}, \mathbf{P})$ quantifies performance or compliance with regard to the design specifications. Examples could be specific fuel consumption, cruise speed, or range.
- Design constraints $\mathbf{C} = constr(\mathbf{X}, \mathbf{P})$ are typically the aircraft's required performance values such as takeoff distance, climb rates, or cruise speed. There are geometric constraints such as limits to wingspan and fuselage diameter and environmental restrictions such as limits to emissions of noise and greenhouse gases or ozone-reducing substances.

Conspicuously missing is the flow variable **F**, which appears in flow simulations. **F** describes the whole flow field and is huge. But **P** is computed from **F**, whose computation is abstracted into $cfd(\mathbf{X}, \mathbf{F}) = 0$, so **F** is just an intermediary without intrinsic value in the design. However, management of **F** is, of course, a technical challenge. The search involves analysis to deduce the properties of a product from its characteristics, as well as synthesis to create a particular design **X** that yields some desired properties $\mathbf{P}(\mathbf{X})$; in other words, optimization in one form or another. Figure 1.16 illustrates the basic elements in this approach.

The dimension of the design parameter set **X** defines the *fidelity* of the configuration representation. Then, depending on the aerodynamic analysis applied to it (L1, L2, or L3), the *fidelity* of the computed flow **F**, as well as its dimension, is correspondingly higher, as indicated in Figure 1.16.

Vehicle properties **P** predicted from higher-fidelity analyses are closer to reality, so they have more localized probability distributions, as indicated by the sizes of the ellipses in the lift-and-drag space. This in turn implies less uncertainty and shorter error bars in the predicted FoMs to the right in Figure 1.16.

Notions of Order and Fidelity

It may be helpful to distinguish between the terms *order* and *fidelity*. An analysis of high order (of accuracy) describes a physical effect in great detail, and a high-fidelity analysis predicts properties accurately. In fact, a low-order analysis might return results of high fidelity. For example, if a primitive geometry – just the planform and camber distribution (no thickness) – were computed in an Euler simulation, the predictions may

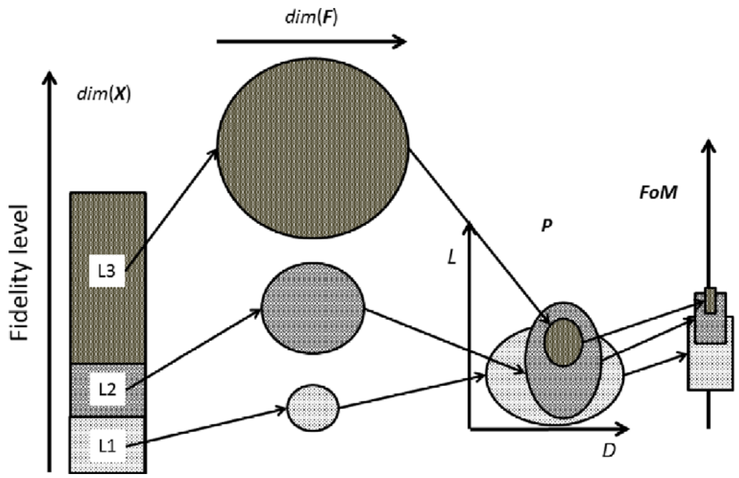


Figure 1.16 Higher-fidelity models give larger data and reduced uncertainty.

well be less accurate than those made by a vortex–lattice method because there will be unrealistic vortices and other separation phenomena from this primitive geometry. The lesson here, of course, is that the fidelity of the prediction method $prop$ should match the fidelity of $\mathbf{X}$.

As an example, the first pass through the design concept loop (Cycle 1) in Figure 1.1 synthesizes the first baseline configuration $\mathbf{X}_{bl}$. With the requirements taken as an initial set of properties $\mathbf{P}$, it derives the basic configuration parameters (e.g. thrust to weight, wing loading, the wing reference area, etc.).

Then, the refinement loop applies these characteristics $\mathbf{X}$ to derive again by analysis properties $\mathbf{P}$, albeit at a higher level of detail (e.g. lift-induced drag from the given wing planform), and then reenters those properties into the configuration development (synthesis) loop to determine a more mature set of characteristics $\mathbf{X}$. Several configurations with different characteristics may share similar properties $\mathbf{P}$, so the evolution of the design to a more mature state also requires down-selection. This means a choice between different candidates that, based on the requirements considered so far, look equally good. Thus, as the design evolves, the requirements are augmented or made stricter or, if no feasible candidates are found, relaxed.

An essential feature of MDO is the presence of design constraints and FoMs of system-level concern. In a typical aircraft conceptual design application, the FoM is either cost or its surrogate, weight, where the aircraft is sized to some specified mission that includes the range and payload requirements. The design constraints are typically the aircraft's required performance such as takeoff distance and climb rates, plus geometric or operational constraints such as a wingspan limit.

A typical application for MDO is the simultaneous aerodynamic and structural optimization of a wing. The wing is defined in terms of geometric variables, and the effects on aerodynamics and structural strength are determined as the geometry is varied. Results are assessed versus a defined FoM, with constraints based on performance, safety, operability, and practicality. The crucial issue in either classical optimization or MDO is the number of design parameters because the workload quickly becomes immense as this number grows.

1.3.2 Problem Complexity and Optimization

The design problem can be posed as an optimization problem, but it is so complex that the formulation is a challenge in itself, and numerical solution will remain beyond the reach of computers in the near future. Therefore, it must be approached by decomposition. Decomposition and software technology is under intense development, as exemplified by papers by M. Giles [8, 9] and the Stanford group around I. Kroo [16]. Different types of software architectures have been proposed, such as collaborative optimization (CO) [2, 15], bi-level integrated system synthesis (BLISS) [27], concurrent subspace optimization (CSO) [31], and many others.

Traditional decomposition leads to subproblems of aerodynamic shape optimization coupled with structural design by simplified constraints such as on wing thickness, limits on wing root bending moment, etc. An example of this will be shown in Chapter 3, indicating that quite detailed constraints must be included for the optimal wing to look like those of contemporary airliners. Even purely aerodynamic shape optimization for clean wings is complex and is in practice carried out using a combination of mathematical tools and engineering know-how. The tools developed and analysed in this work are described in Chapter 9. Thus, although technically a single-discipline optimization, it is still complex enough that decomposition and other methods employed in MDO may be useful.

The Curse of Dimensionality

Consider the basic set of six design parameters commonly used in sizing the wing (see Figures 1.1 and 1.4): thrust-to-weight T/W, wing loading W/S, and wing aspect ratio AR, taper ratio λ, sweep Λ, and thickness t/c. In the language of experimental design, a full factorial design requires a minimum of $3^6 = 729$ data points to span the design space, and $5^6 = 15,625$ would improve accuracy. Each data point represents a different airplane and requires analysis for aerodynamics, propulsion, weights, sizing, and performance. To better optimize an aircraft in the next loops in Figure 1.1, one includes additional design parameters to more precisely specify the actual shape, including wing planform breaks, nacelle locations, tail locations, fuselage fineness ratio, wing design lift coefficient (or camber), wing thickness distribution, engine bypass ratio or propeller diameter, etc. As additional design variables are added, the number of required data points (i.e. aircraft parametric evaluations) rapidly spirals out of control. This brings into focus the issues of information and time, sometimes labeled the "curse of dimensionality," addressed in D. Böhnke's PhD dissertation [1]. Some relief for small-dimensional design spaces is brought by sampling schemes developed for experimental design, such as Latin hypercube, but not enough to cast off the curse.

Decomposition of the design space offers potential reduction of the computational workload. In practice, engineers know that some analysis results may be rather insensitive to some selected design variables. Many design variables are not very interdependent (“weakly coupled”) and can be optimized separately. The designer partitions a large engineering design optimization problem into a number of smaller subproblems, formulated so that their couplings can be relaxed only to be ever better satisfied as the candidates converge to the optimum.

This decomposition allows separate optimizations with private variables in the subproblems. The subproblems in turn may also be broken into weakly interconnected models, creating a hierarchical structure to the optimization process.

As an example of a particular decomposition, consider an aerodynamic wing-shape optimization for minimizing drag, where the weight of a candidate shape is minimized by a structural optimization tool. This realizes a “Stackelberg equilibrium” in a game played by the shape optimizer and the structural optimizer.

$$\min_{x} Drag(x) \tag{1.6}$$

$$s.t. \quad g(x, y(x)) \leq 0 \text{ where}$$

$$y(x) = arg \min_{y} Weight(x, y) \tag{1.7}$$

$$s.t. \quad \text{structure tolerates airloads}$$

Here, x represents the public parameters governing wing surface shape and y represents the private parameters of the structural mechanics (position, thickness, etc., of ribs, spars, skin). g represents shape constraints such as maximal wingspan. Each evaluation of y requires the resolution of a structural mechanics optimization problem.

1.3.3 Basic Elements of Weakly Coupled MDO

The usual development approach of MDAO tools uses established disciplinary codes, often referred to as “legacy codes,” in a “weak” coupling mode. For example, in the present treatment of aero-elastic and structural dynamics problems, predominantly linear aerodynamic methods are employed, dynamic structure problems are treated in the frequency domain, and the flow/structure coupling is made by passing analysis results back and forth between aerodynamics and structural analyses. The couplings with flight dynamics and flight control are made unidirectionally. The new treatment basically must evolve out of the present capabilities in order to reduce risks and to ensure the acceptance of users in the aircraft definition and development processes. However, many of the required strategies for dealing with such complex systems have yet to be developed.

The property variables **P** from the corresponding multidisciplinary analysis problem for the design variables **X** are subject to the optimizer that minimizes an objective function, a single FoM, composed from the whole set of **FoM** considered.

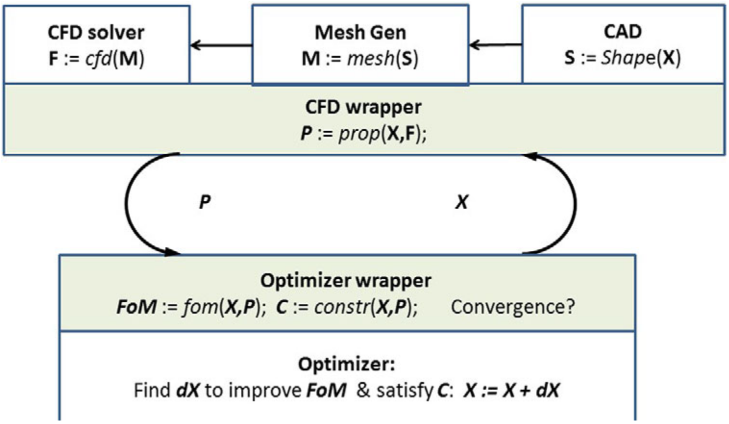


Figure 1.17 Shape optimization, with mesh regeneration.

$$\begin{aligned} \min_{\mathbf{X}} FoM &= fom(\mathbf{X},\mathbf{P}) \\ \text{subject to constraints } \mathbf{P} &= prop(\mathbf{X}) \\ \mathbf{R} &= constr(\mathbf{X},\mathbf{P}) \le \mathbf{0} \end{aligned} \tag{1.8}$$

Note that the inequality constraints also include equalities from a construction such as $f \le 0, -f \le 0$. Figure 1.17 shows a common aerodynamic shape optimization scheme with loosely coupled modules, the CFD module comprising a CAD program, a mesh generator, and the CFD solver proper. The CAD program creates the shape **S** of the wing from the geometric parameters in **X**. The mesh generator makes the computational mesh **M** around **S**, and finally the flow solver computes the flow **F** on **M**. The CFD module is driven by an application program interface (API) exposed by the “wrapper” to external modules. The CFD “wrapper” also computes FoMs and constraints from **F** and exports them to the optimizer, which finds an increment **dX** to improve the FoM and satisfy the constraints. The new parameters are exported to the CFD module for the next iteration. To operate efficiently, the optimizer needs gradients of the FoMs and constraints. The gradients can be computed by numerical differencing, with one run for each parameter, so for Np parameters, the flow solver must be run $Np+1$ times. Modern flow solvers often provide calculation of derivatives by solution of an adjoint partial differential equation (PDE) problem, which reduces the work significantly for large Np. See the book’s website for an overview of the mathematics involved. Chapter 3 gives an example of induced drag minimization where the aero-analysis is done by the vortex lattice method.

Current State-of-the-Art Develpoment

The current state of the art is exemplified in Section 9.3.3, which reports on the results of mathematical shape optimization for drag of the Common Research Model wing.

The baseline geometry has been made available by Boeing and AIAA as a realistic test case for developers of MDO. The group of J. Martins at the University of Michigan produced the results we quote with a state-of-the-art software approach applicable to real multidisciplinary design exercises. Their gallery of applications includes such diverse systems as optimization of the shape and structure of wings, structural mechanics of satellites, and lithium-ion batteries [25]. The speed of optimization algorithms depends crucially on the availability of gradients of the objective with respect to the design variables. For aerodynamic shape optimization, the differentiation must involve the effect of surface shape on the volume grid, which in turn affects the flow solution, etc. Algorithms for the differentiation of computer codes [5] have been around for decades and are important ingredients in the overall software system. Progress in MDO requires flexible and general APIs to allow differentiation through the whole chain of analysis modules; the MSES airfoil analysis and design system described in Chapter 7 uses analytically computed derivatives for efficient solution of the flow problem and as ingredients in the shape design task. The Martins' group `OpenMDAO` software bundle [10] takes this approach to a level where it is applicable to large complex systems.

1.4 Aerodynamic Design and CFD

Let us summarize the discussion so far. At its earliest stage, aircraft design begins with the specifications of the flight mission and a request that starts with a blank-sheet design. With an idea for a concept expressed as a sketch, generalists set in motion the parametric process using the L0 empirical/handbook methods described in Section 1.1.4. These are the most suitable for this boot-strapping process that, using only a sketch or even a sized planform, must "guess" what the actual weight is that must be lifted into the air. The best tools of this type are industry-owned and proprietary because they have been honed through many years of industrial know-how and experience.

This book focuses on the aerodynamic tools and tasks used to evolve a baseline into a mature and viable shape – a feasible design – with enough detail that could, for example, be machined into a wind tunnel model or a remotely flyable demonstrator. CFD is the tool for this task.

1.4.1 Tasks and CFD Tools

Thus, the major task of aerodynamics is to define the overall shape of the vehicle in order to fulfill the performance demands of the flight envelope. At its extremes are found load cases that are critical for structural dimensioning. In addition, fly-ability and controllability of the vehicle must be analyzed (see Figure 1.18). More than a pure aerodynamic optimization, the shape definition process must take into account structural constraints in an aero-structural optimization, as well as stability

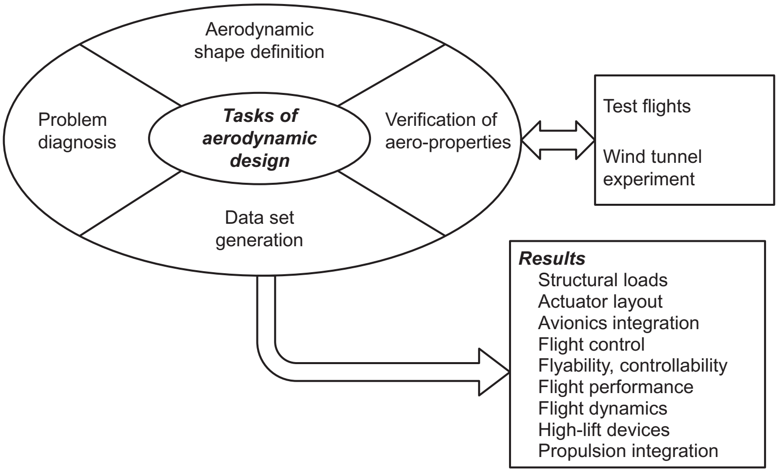


Figure 1.18 The tools, tasks, and results of the aerodynamic design process.

and control characteristics. Hence, aerodynamic data set generation is a task that enables integration with other disciplines and problem diagnosis when performance requirements are not met. Once the design detail have advanced sufficiently far, models can be built. Other equally important tasks and processes are, in concert with wind tunnel and flight testing, the verification of the aerodynamic design and its guaranteed performance.

Senior Technical Fellow at Boeing Commercial Airplanes Philippe Spalart [28] gives the industry perspective on the role and challenges of CFD in building aircraft. It resonates with the issues of aerodynamic design that we spell out here at a pedagogical level. With much in common with Spalart's views, Figure 1.18 outlines our perspective on the overall tasks of aerodynamic design. Let us enumerate them in some detail. Typical design applications where CFD can make major contributions are as follows.

1. *Aerodynamic shape definition* (i.e. its lofting and analysis).
   - Select optimum airfoils, wing lofting, and empennage configuration for performance. Chapters 8 and 9 cover these topics.
   - Define the outer surface shape of the airframe to fulfill the aerodynamic requirements regarding lift, drag, loads, stability criteria, etc., by sizing, shaping, and positioning its various geometric components, taking into account propulsion integration, structures, and their volumetric demands.
2. *Performance data set*: compute force and moment data to estimate lift, drag, and moments over the flight envelope of the vehicle.
   - *Control surfaces*: determine aerodynamic coefficients, force, and moment data to evaluate stability and control derivatives.

  - Verify performance, control, and handling characteristics in a flight simulator. Chapter 10 covers these topics.
3. *Air-loads data set*: compute surface pressure to determine structural loading and aero-elastic impacts, including the likely loss of aerodynamic performance and control surface effectiveness due to structural deformation under load (static aero-elasticity). Chapter 11 covers this topic.
4. *Problem diagnosis*: understand and solve *problems* discovered in wind tunnel or flight testing.
   - Poor flying qualities that cannot be cured by control laws implemented in the flight control system must be remedied through aerodynamic redesign. Chapter 10 covers this topic.

Some of the applications concern *attached flow* (e.g. cruise shape definition). Many of the others involve *separated flow*, such as at the extremes of the flight envelope, where only Reynolds-averaged Navier–Stokes (RANS) is a viable flow model. For example, the loads that determine the sizing of the structures usually occur at separated flow conditions well away from the cruise design point. Chapter 2 explains in detail the physics of attached and separated airflow and describes the various appropriate mathematical models.

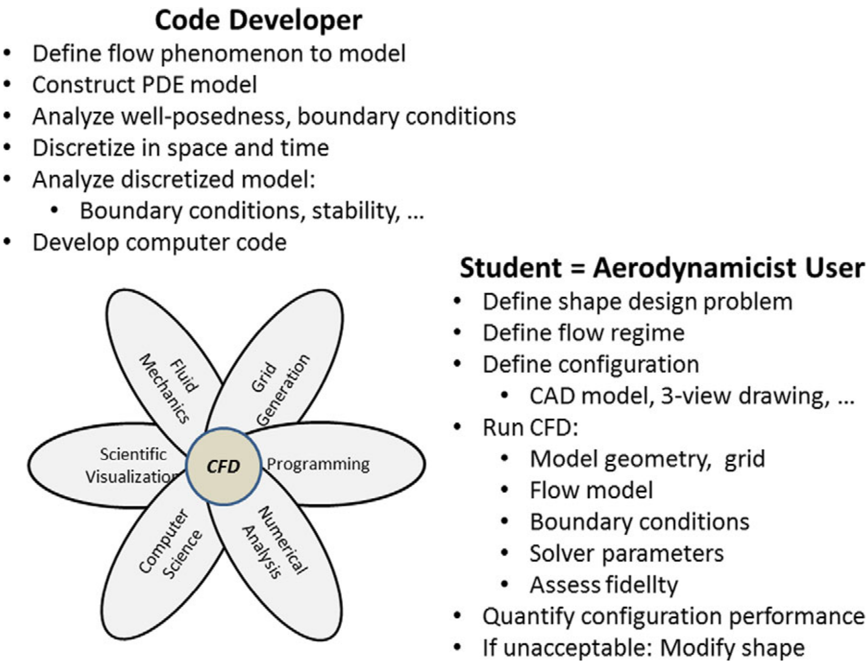
1.4.2 CFD Workflow and User Awareness

CFD is the science of producing numerical solutions, by computational methods, to a system of PDEs that describe fluid flow, or airflow in the case of aerodynamics. The purpose is to better understand, qualitatively and quantitatively, flow phenomena in order to improve upon engineering design.

Teaching User Awareness: The Informed User

As is shown in Figure 1.19, CFD draws upon elements from six related disciplines: fluid mechanics (of which aerodynamics is a part), numerical analysis, programming principles, computer science, grid generation, and scientific visualization.

The code developers described in Figure 1.19 are hard at work to improve their products, but it is still necessary for the CFD engineer to *understand* what goes on under the hood. For example, CFD codes do not always work. They may give up and produce no solution at all, or they may produce a flow field in significant disagreement with the real flow. The user must assess the *quality* of the solution, and modify the parameters that control the code to give a *reliable* solution. This is what an *informed* CFD user must do, and we call it *CFD due diligence*. Philippe Spalart [28] calls for more user awareness in industrial CFD:



Code Developer

- Define flow phenomenon to model
- Construct PDE model
- Analyze well-posedness, boundary conditions
- Discretize in space and time
- Analyze discretized model:
  - Boundary conditions, stability, ...
- Develop computer code

Student = Aerodynamicist User

- Define shape design problem
- Define flow regime
- Define configuration
  - CAD model, 3-view drawing, ...
- Run CFD:
  - Model geometry, grid
  - Flow model
  - Boundary conditions
  - Solver parameters
  - Assess fidellty
- Quantify configuration performance
- If unacceptable: Modify shape

Figure 1.19 Disciplines in CFD and tasks of the code developer and typical user – the student as aerodynamicist.

> *The quality of CFD answers depends at least on three factors: the code, the available computer resources (which limit the grid resolution and number of iterations), and the user.*

In addition, codes should provide more actionable information of direct importance to the designer:

> *Another support for awareness of physics …will be available if and when a rigorous definition of induced drag, wave drag, and parasitic drag from viscous flow fields is established. These concepts are constantly used by designers …*

Greater automation is called for in the overall workflow. Even more important is automation of the numerical solution process. Grid adaptation is a case in point, which is a challenge for the resolution of boundary layers, shocks, and vortices. But user know-how is key, no matter how advanced the code and how fast the computer. Overconfidence and undercompetence in CFD must be addressed through education. Sufficient emphasis must be placed on the flow models, the numerical methods, and hands-on experience in CFD codes. The student must become an informed CFD user with awareness of the power and limitations of their tools. Spalart proposes that, at the same time, curricula should

…temper the erosion of classical aerodynamic knowledge in the younger generations.

The European Research Community on Flow, Turbulence and Combustion (ERCOFTAC) has put out a set of very helpful *Best Practice Guidelines for CFD* [7], available via the web. Since a CFD code offers a variety of turbulence models at the touch of a button (see Chapter 6), it may be tempting to believe that bad results are usually caused by inadequate choice of turbulence model. However, as made very clear by the Guidelines, as often as not the problem lies with the basic ingredients of grid quality, convergence level of iterative schemes, and choice of boundary conditions.

An *informed user*, applying *due diligence*, will ascertain – with a significant degree of certainty – that the computed flow field agrees with the real flow. This calls for:

1. Choosing the CFD fidelity level and numerical modeling appropriate to the shock waves and vortical features of the problem at hand (see Chapters 3 and 4, and hands-on tutorials on VLM and DemoFlow).
2. Modeling the geometry and generating a grid of sufficient quality and resolution to represent the vehicle and the flow under investigation adequately (see Chapter 5 and hands-on modeling and automatic grid generation tutorials).
3. Verifying convergence to steady state, if it exists, and if not, computing the unsteady flow with sufficient time accuracy (see Chapter 6 and its associated hands-on tutorials).
4. Visualization and analysis of the computed solution to verify reliably that the chosen level of physical modeling is appropriate (see Chapters 4 and 6 with hands-on examples).

Workflow

Once competent in CFD due diligence, the user can proceed to apply CFD to problems in aircraft aerodynamics, as outlined in Figure 1.19, as follows.

1. Shape design and performance analysis of *airfoils*: Chapters 7 and 8 focus on transonic airfoils, with hands-on running of MSES and RANS for active learning of mapping of airfoil shapes to performance.
2. Shape design and performance analysis of *clean wings*: Chapters 9 and 10 focus on the wing shape secondary parameters in Table 1.3, with hands-on running of RANS for active learning of wing geometry mapping to performance. The studies include twist, camber, and thickness scheduling for the CRM wing to improve flow over root and tip.
3. Development of a *full configuration* with acceptable flying qualities and aero-elastic behavior: Chapter 10 develops the TCR design proposal further in Cycle 3, including analysis of stability and flying qualities in flight simulation using multi-fidelity aerodynamics modeling. Chapter 11 discusses how the wing shape in flight can be predicted from its jig shape.

CFD is the main tool in all of the above actions, which we call the *CFD workflow*. The text uses the EDGE code as generic examples of concepts that apply to most CFD

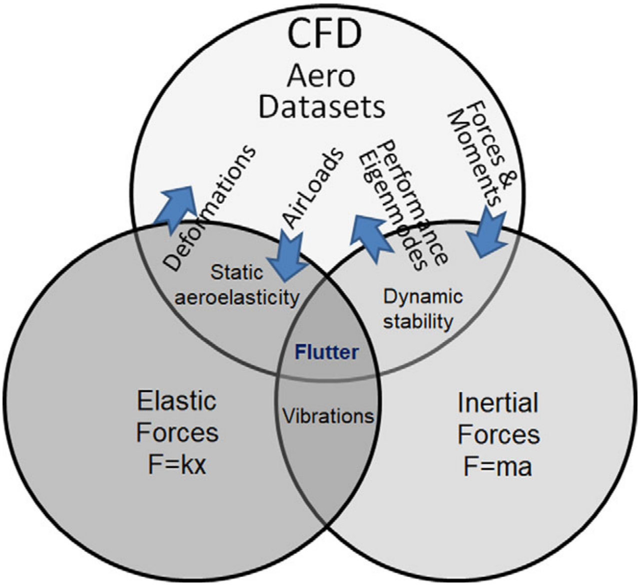


Figure 1.20 CFD results as used in several design tasks.

codes in the hope that the similarities outweigh the differences in the code(s) available to the student. We abstain from discussing the peculiarities of any single CFD computer program.

Data Exchange with Other Disciplines

A successful design must guarantee that the airplane behaves as expected for all possible flight states (i.e over the entire *flight envelope*). It must be controllable by the pilot, its structural integrity must be guaranteed, and its performance in terms of speed, climb rate, payload capacity, fuel consumption, field requirements for take-off and landing, etc., must agree with specifications. Only a multidisciplinary analysis can provide such a guarantee, as is suggested in Figure 1.20. The airplane behavior can be predicted from the *aerodynamic data set*, with its tables of the forces and moments exerted on it from the air, inertia, and gravity, in the different flight states. The data can be obtained through measurements or CFD computations. The first simplification is to assume that the aircraft is rigid. The aerodynamic forces and moments computed by CFD are applied to the six degrees of freedom model of a rigid body, thus allowing the study of dynamic stability. This enables investigation of flying qualities via the eigenmodes of motion, as explained in Chapter 10. The next approximation is to allow flexibility and to take into account static aero-elastic deformation, where structural mechanics interacts with CFD through the airloads (surface pressure, possibly unsteady) on the wings and control surfaces. This is the *loads data set*. As the design matures, increasingly rich data sets generated by the analyses are used for evaluating the performance of the concept.

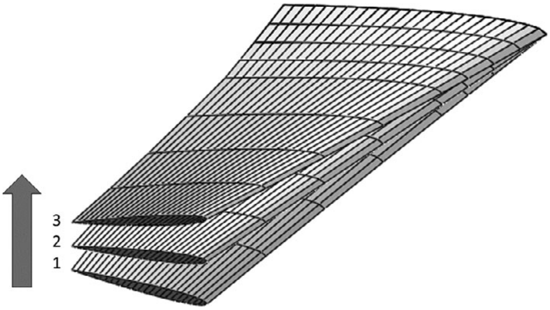


Figure 1.21 Deformations of a wing under aero-loads.

Static Aero-Elastic Effects

CFD and structural analysis need to be integrated, because the aerodynamic loads size the structure and influence the mass of the aircraft, and therefore, its cost and performance.

Through the design phase of an aircraft, the fidelity of the structural model could increase from a simple approximation, such as a beam model, to a sophisticated finite-element model later on. Typically, for the static deflection of the wing from its jig shape to its flight shape, the aero-structural coupling is done in a loose fashion and often converges in just a few iterations, as is indicated in Figure 1.21 and explained in Chapter 11. Dynamic load interactions, including flutter and vibrations, call for time-dependent or time-harmonic CFD analysis to be coupled with a structural module, and this is beyond the scope of this book.

1.4.3 Challenges to Improving Performance

Improvements in aerodynamics (see Figure 1.22), as well as materials and propulsion, can contribute modest gains in the overall productivity and quality of the aircraft.

Fuel reduction is a long-standing goal in improved performance. It can result from concurrent adaption of advanced technologies in aerodynamics by increasing the lift-to-drag ratio, in structures and materials by decreasing the overall weight, and in systems and engine design by reducing the specific fuel consumption. The specific range (Eq. (1.1)) illustrates quantitatively how the different aircraft subsystems influence fuel consumption.

In this book, we focus on the aerodynamics, and Figure 1.22 highlights some aerodynamic design tasks involved with five different classes of aircraft: propeller-driven commuter, conventional jet airliner, blended wing–body transport, business jet, and jet fighter. Many of the tasks are common to all classes, but some are specific to particular classes. A number of these tasks will be delved into in Chapters 9 and 10.

For example, improvements in airframe technology, such as high-speed airfoil and wing design, can extend the operational boundaries of the aircraft by delaying the onset of buffet and increasing the lift at maximum cruise speed. This can mean reducing wave and friction drag and enhancing the maximum operating Mach number, thus improving flight performance and allowing more flexible conditions for operating the aircraft.

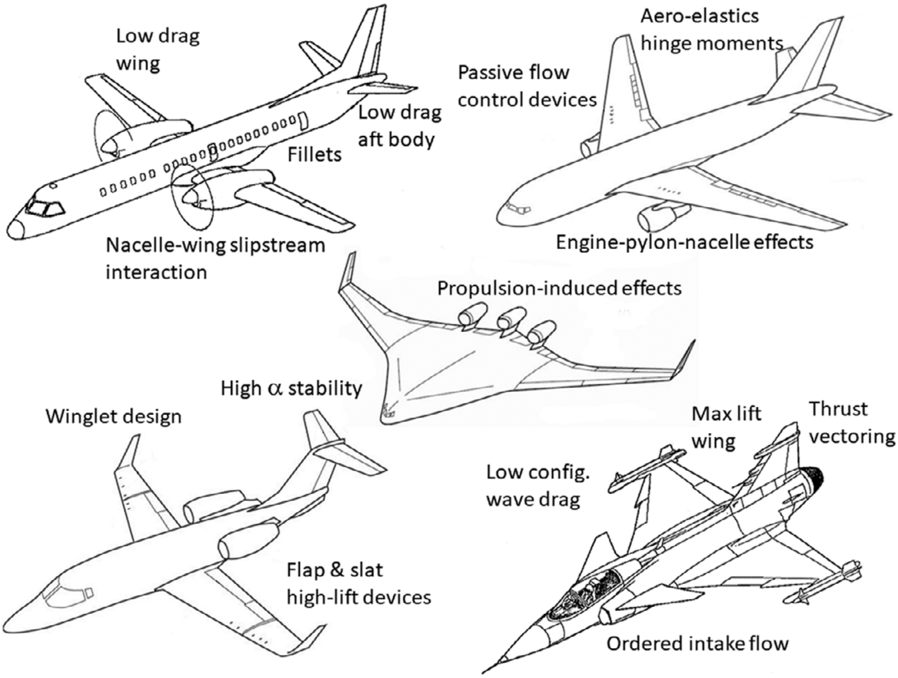


Figure 1.22 Five different classes of aircraft pose challenging aerodynamic design tasks.

Advanced wing-tip devices decrease drag, increase the maximum range, and relax the limitations on take-off weight. Better integration of propulsion into the airframe reduces interference drag. Means to enhance lift and decrease lift-induced drag include using wings with higher aspect ratio, variable camber, and smart wings that change shape with flight regime. Better shock-wave boundary-layer control delays the onset of buffet and drag divergence. Greater regions of laminar flow over the wing, the tail, and nacelles translate into reduced friction drag, as does overall better management of the turbulent flow.

With this introduction to the subjects in the book, we are ready to look in the next chapter at the types of flow fields that the aerodynamic designer strives to exploit.

1.5 Learn More by Computing

Gain hands-on experience of the computational tools for the topics in this chapter by working with the on-line resources. Exercises, tutorials, and project suggestions are found on the book website www.cambridge.org/rizzi. In particular, work the tutorial introducing the mathematical shape optimization. Software used to compute many of the examples shown is available from http://airinnova.se/education/aero-dynamic-design-of-aircraft

References

[1] D. Böhnke. *A Multi-Fidelity Workflow to Derive Physics-Based Conceptual Design Methods*. Doctoral thesis, DLR, August 2014.

[2] R. Braun. *Collaborative Optimization: An Architecture for Large-Scale Distributed Design*. PhD thesis, Stanford University, May 1996.

[3] J. Chuprun. Wings. Technical report, 1980. AIAA-Paper-80-3031.

[4] P. D. Ciampa and B. Nagel. AGILE the next generation of collaborative MDO: Achievements and open challenges. 2018 Multidisciplinary Analysis and Optimization Conference, June 2018. AIAA-Paper-2018-3249.

[5] G. Corliss, C. Faure, A. Griewank, L. Hascoët, and U. Naumann, editors. *Automatic Differentiation of Algorithms: From Simulation to Optimization*. Springer, 2002.

[6] P. DellaVecchia, P. Ciampa, P. S. Prakasha, B. Aigner, and I. vanGent. MDO framework for university research collaboration: AGILE academy initiatives and outcomes. 2018 Multidisciplinary Analysis and Optimization Conference, June 2018. AIAA-Paper-2018-3254.

[7] Ercoftac. www.ercoftac.org/publications/.

[8] M. B. Giles. Aerospace design: A complex task. Technical Report, Computing Laboratory, Oxford University, July 1997.

[9] M. B. Giles and N. A. Pierce. An introduction to the adjoint approach to design. *Flow, Turbulence and Combustion*, 65: 393–415, 2000.

[10] J. S. Gray, J. T. Hwang, J. R. R. A. Martins, K. T. Moore, and B. A. Naylor. OpenMDAO: An open source framework for multidisciplinary design, analysis, and optimization. *Structural and Multidisciplinary Optimization*, 2019. Available from http://mdolab.engin.umich.edu.

[11] D. W. Hall. To fly on the wings of the sun: A study of solar-powered aircraft. Technical Report Vol. 18, Lockheed Horizons, Lockheed Corp., Burbank, CA, January 1985.

[12] M. Hepperle. The sonic cruiser – a concept analysis. Presented at Aviation Technologies of the XXI Century: New Aircraft Concepts and Flight Simulation. Aviation Salon, ILA Berlin Air Show, Berlin, May 2002.

[13] D. E. Hoak et al. The USAF Stability and Control DATCOM. Technical Report TR-83-3048, Air Force Wright Aeronautical Laboratories, October 1960 (revised 1978).

[14] SUMO homepage. Available from www.larosterna.com/sumo.html.

[15] I. Kroo and V. Manning. Collaborative optimization: Status and directions. AIAA Paper 2000-4721, September 2000.

[16] I. M. Kroo. MDO for Large-Scale Design. In *Multidisciplinary Design Optimization: State-of-the-Art* SIAM, 1997, pp. 22–44.

[17] E. Obert. *Aerodynamic Design of Transport Aircraft*. IOS Press, 2009.

[18] A. C. Piccirillo. *Elegance in Flight: A Comprehensive History of the F-16XL Experimental Prototype and Its Role in NASA Flight Research*. NASA Aeronautics Book Series, 2014. Available from www.nasa.gov/ebooks.

[19] D. P. Raymer. *Aircraft Design: A Conceptual Approach*. American Institute of Aeronautics and Astronautics, 6th edition, 2018.

[20] A. Rizzi. Modeling and simulating aircraft stability and control – the simsac project. *Progress in Aerospace Sciences*, 47(8): 573–588, 2011.

[21] A. Rizzi, P. Eliasson, T. Goetzendorf-Grabowski, J. B. Vos, M. Zhang, and T. S. Richardson. Design of a canard configured TransCruiser using CEASIOM. *Progress in Aerospace Sciences*, 47(8): 695–705, 2011.

[22] A. Rizzi and J. B. Vos. Preamble to special issue – modeling and simulating aircraft stability and control. *Progress in Aerospace Sciences*, 47(8): 571–572, 2011.

[23] J. Roskam. *Airplane Design Parts I–VIII*. DAR Corporation, 1985.

[24] D. M. Ryle. *High Reynolds number subsonic aerodynamics*, chapter Paper No. 6, pages 6–1 – 6–115. AGARD Lecture Series LS-37-70. AGARD, Neuilly-sur-Seine, France, June 1970.

[25] A. Sgueglia, P. Schmollgruber, N. Bartoli, E. Benard, J. Morlier, J. Jasa, J. R. R. A. Martins, J. T. Hwang, and J. S. Gray. Multidisciplinary design optimization framework with coupled derivative computation for hybrid aircraft. *Journal of Aircraft*, 2020 (in press).

[26] A. M. O. Smith. Wing design and analysis – your job. In T. Cebeci, editor, *Numerical and Physical Aspects of Aerodynmic Flows*. Springer Science + Business Media, 1984, pp. 41–59.

[27] J. Sobeiszczanski-Sobieski, J. Agte, and R. Sandusky. Bi-level integrated system synthesis (BLISS). Presented at *AIAA Symposium on Multidisciplinary Analysis and Optimization*, St. Louis, MO, September 1998. AIAA-1998-4916.

[28] P. R. Spalart and V. Venkatakrishnan. On the role and challenges of CFD in the aerospace industry. *Aeronautical Journal*, 120(1223): 209–232, 2016.

[29] E. Torenbeek. *Synthesis of Subsonic Airplane Design*. Springer Netherlands, 1982.

[30] J. E. Williams and S. R. Vukelich. *The USAF Stability and Control Digital Datcom*. Air Force Wright Aeronautical Laboratories, 1979.

[31] B. Wujek, J. Renaud, and S. Batill. A concurrent engineering approach for multidisciplinary design in distributed computing environment. In N. Alexandrov and M. Y. Hussaini, editors, *Multidisciplinary Design Optimization: State of the Art*. SIAM, 1997, pp. 189–208.