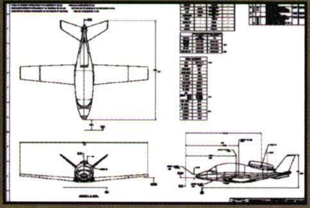
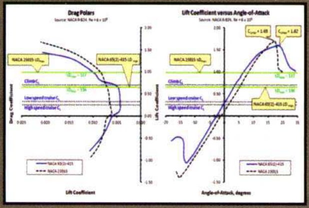
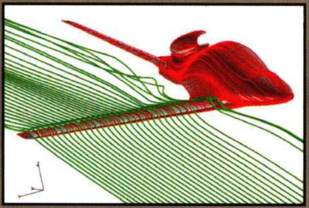
GENERAL AVIATION AIRCRAFT DESIGN

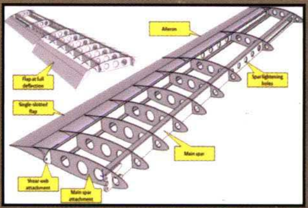
APPLIED METHODS AND PROCEDURES

SNORRI GUDMUNDSSON









GENERAL AVIATION AIRCRAFT DESIGN: APPLIED METHODS AND PROCEDURES

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CHAPTER

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1.1 INTRODUCTION

What is a *design*? It is probably appropriate to begin a book on design by discussing the term itself, especially considering the concept is often erroneously defined and sometimes even characterized through zeal rather than a true understanding of its meaning. The author recalls a past interview with a renowned designer who, during a TV interview, was asked to define the term. The show that ensued was a disappointing mixture of superficial self-importance and an embarrassing unpreparedness for the question. Following an artful tiptoeing around the issue the concluding response could be summarized as; "well, everything is designed." No, nothing could be further from the truth: not everything is designed. Some things are designed while other things are not. When self-proclaimed designers have a hard time defining the term properly it should not be surprising when laypeople misuse the word and apply it to things that are clearly not designed. The least we can expect of any designer is to accurately define the concept to laypeople, some of whom have openly demonstrated an inability to distinguish a *regular pattern* from a *design*.

Any attempt at defining the word properly requires an insight into how the brain perceives the geometry that surrounds us. It is a question of great intrigue. How can the brain tell apart a clamshell and a cloud, or a raccoon and a road? This is achieved using the brain's innate ability called *rapid pattern recognition*, common to all animals. It is one of the most important biological traits in any species that relies on optics as a primary sensory organ. In fact, this ability, a consequence of a biological evolution lasting over hundreds of millions of years, is imperative to the survival of the species. Its most important strength is that it allows animals to make a distinction between the facial features of a mother and the silhouette of a dangerous predator (for instance, see [1]).

If you see a face when you look at the front end of a typical car, or the silhouette of people or animals when looking at rock formations or clouds, you should know that this is your brain's pattern recognition subroutine working overtime. It is desperately trying to construct a recognizable image from any pattern that hits the retina to help you quickly identify friends from foes. The faster a member of a species can accomplish this feat, the greater is the chance it may escape a dangerous predator or identify a concealed prey, providing a clear evolutionary advantage. It helps a falcon see a rodent from great heights as much as it helps an antelope identify a lurking lion. However, just as rapid pattern recognition is capable of discerning predator and prey; it can also play tricks with the brain and cause it to assemble random patterns into images of easily recognizable things that are simply not there. This condition is called *apophenia*. The lack of public education on this elementary biological function is stunning and renders some laypeople altogether incapable of realizing that the interplay of dark and light areas on their toast or potato chip that looks like their favorite celebrity is not a design but only a random pattern the brain has managed to assemble into a recognizable shape. Deprived of knowledge to know any better, many yield to wishful thinking and allow the imagination to run wild.

In short, a *regular pattern* is a combination of geometrical, physical, or mathematical features that may or may not be random, but "appears" either repetitious or regular through some characterization, such as learning. In fact, our environment is jam-packed with regular patterns. The repetition (or regularity) of a pattern allows the brain to separate it from the truly random background. People, familiar with the term "design," erroneously deduce that since a pattern appears to be regular it must be designed, when in fact it is not. A *design* is a pattern of geometrical, physical, or mathematical features that is the consequence of an intent and purpose. A design requires an originator who intended for the pattern to look a certain way so it could serve its proposed purpose. This way, *a design is a subset of regular patterns and one that has a preconceived goal, requires planned actions to prepare, and serves a specific purpose*.

Consider the natural shapes in Figure 1-1. The mountain range to the left was not designed but formed by the mindless forces of nature. There was no preconceived plan that the range should look this way and not some other way. It just formed this way over a long time – it is a random but repetitious pattern. The contrails that criss-cross the sky over the Yosemite National Park, in the right image, were not planned either. They are a consequence of random departure times of different airplanes in different parts of the USA, headed in different directions at different altitudes. While the arrangement of the airway system is truly designed it was not conceived with the contrails in mind but for a different purpose altogether. No one planned the airway system so this pattern would form over El Capitan in this fashion and not some other. No one was ever tasked with figuring out that this particular day the winds aloft would allow the pattern to stay so regular. Its appearance is nothing but a coincidence. The geometry of the contrails, just like the mountain range in the left image, is the consequence of random events that were not designed. Claiming these are designs, automatically inflicts a burden-of-proof obligation on the petitioner: Show the plans, the originator, and explain the purpose and, if unable to, simply call it by its proper name until such plans surface: a pattern is a pattern until it can be shown to be a design.

FIGURE 1-1 Examples of random patterns. The mountain range to the left is shaped by the random forces of nature. The pattern of contrails over the Yosemite National Park is the consequence of random departure times of the aircraft involved that are influenced by random decisions of air traffic controllers. There is absolutely no intentional intelligence that forms these shapes. They just appear that way. *(Photos by* Snævarr Guðmundsson*)*

With the philosophy of design behind us, we can now focus on the primary topic of this book – the design of aircraft, in particular General Aviation aircraft. According to the Federal Aviation Administration, the term *General Aviation aircraft* (from here on called GA aircraft) refers to *all aircraft other than airlines and military operations* [2]. This includes a large body of aircraft, ranging from sailplanes and airships to turbofan jets. Most aircraft are designed to comply with strict regulatory standards. In the USA these are managed and maintained by the Federal Aviation Administration (FAA). In Europe the standards are set by the European Aviation Safety Agency (EASA). These standards are similar in most ways, which results from an effort between the two agencies to harmonize them. Table 1-1 lists a number of standards for selected classes of aircraft.

In the USA, a light sport aircraft (LSA) is treated differently from an aircraft certified to 14 CFR Part 23 or 25. Instead of a direct involvement in the certification process, the FAA accepts compliance based on so-called consensus standards. These standards are neither established nor maintained by the agency itself but by some other organization. Some of these are really "watered down" FAA rules that are far less burdensome to comply with than the originals. This can partially be justified on the basis that the airplanes they apply to are much simpler than regular aircraft.

The acceptance of consensus standards (LSA) is effectively based on the "honor system." In other words, a manufacturer tells the FAA its product complies with the applicable standards and, in return, receives an airworthiness certificate. This is done as long as no "issues" surface. The system is a form of "self-regulation" and is designed to keep the FAA out of the loop. The LSA industry recognizes that responsible compliance is the only way to avoid more burdensome regulations. According to FAA officials in 2012, this system has been more or less problem free, excluding one instance [3].

Currently, the American Society for Testing and Materials (ASTM) is the primary organization that establishes and maintains consensus standards for LSA. ASTM has developed a number of standards that apply to different types of aircraft. The FAA accepts some of these in lieu of 14 CFR. Which standard ultimately depends on the subclass of aircraft (aircraft, glider, gyrocopter, lighter-than-air, powered parachutes, and weight-shift control)

TABLE 1-1 Certification Basis for Several Classes of Aircraft

Class	Regulations	Comments
General Aviation	14 CFR Part 23 (USA) CS-23 (Europe)	
Commercial Aviation	14 CFR Part 25 (USA) CS-25 (Europe)	
Sailplanes	14 CFR 21.17(b) (USA) CS-22 (Europe)	14 CFR 21.17(b) allows the FAA to tailor the certification on a need-to basis to sailplanes. Then, by referring to AC 21.17-2A, the FAA accepts the former JAR-22 as a certification basis, which have now been superceded by CS-22.
Airships	14 CFR 21.17(b) (USA) CS-30 and CS-31HA	14 CFR 21.17(b) allows the FAA to tailor the certification on a need-to basis to airships.
Non-conventional Aircraft	14 CFR 21.17(b) (USA) CS-22 (Europe)	14 CFR 21.17(b) allows the FAA to tailor the certification on a need-to basis to non-conventional aircraft.
Light Sport Aircraft (LSA)	Consensus (USA) CS-LSA (Europe)	See discussion below regarding LSA acceptance in the USA.

and on a number of specific fields (design and performance; required equipment; quality assurance; and many others). For instance, for the subclass *aircraft*, design and performance is accepted if it complies with ASTM F2245, required equipment must also comply with ASTM F2245, but quality assurance must comply with ASTM F2279, maintenance and inspection with ASTM F2483, and so on. Gliders, gyroplanes, and other light aircraft must comply with different ASTM standards. The matrix of requirements can be obtained from the FAA website [4].

While this book will mostly focus on the design of new GA aircraft, other classes of aircraft will be discussed when needed. The designer of GA aircraft should be well rounded in other types of aircraft as well, a point that will be made repeatedly throughout this book.

GA aircraft certified under 14 CFR Part 23 are subject to a number of limitations as stipulated under 14 CFR Part 23.3-Airplane categories. The regulations place aircraft to be certified into four categories; *normal*, *utility*, *aerobatic*, and *commuter*. These categories must abide by the restrictions listed in Table 1-2. With the exception of the commuter category, an aircraft may be certified in more than one category provided all requirements of each are met.

New aircraft are designed for a variety of reasons, but most are designed to fulfill a specific role or a mission as dictated by prospective customers. For economic reasons, some aircraft (primarily military aircraft) are designed to satisfy more than one mission; these are *multi-role* aircraft. Others, for instance homebuilt aircraft, are designed for much less demanding reasons and are often solely based on what appeals to the designer.

No matter the type of aircraft or the reason for its design, specific tasks must be completed before it can be built and flown. The order of these tasks is called the *design process*. This process is necessitated by the fact that it costs a lot of money to develop a new aircraft. Organizations that develop new aircraft do not invest large amounts of funds in a design project until convinced it can perform what it is intended to. A design process makes this possible by systematically evaluating critical aspects of the design. This is primarily done using mathematical procedures, as well as specific testing of structural configuration, materials, avionics, control system layout, and many more.

The order of the tasks that constitute the design process may vary depending on the company involved. Usually there is an overlap of tasks. For instance, it is possible that the design of the fuselage structure is already in progress before the sizing of the wing or stabilizing surfaces is fully completed. Generally, the actual process will depend on the size and maturity of the company in which it takes place and the order of tasks often varies. However, there are certain steps that must be completed in all of them; for instance, the estimation of weight; sizing of lifting surfaces and the fuselage; estimation of performance; and other essential tasks.

In mature companies, the design process is managed by individuals who understand the big picture. They understand the scope of the project and are aware of the many pitfalls in scheduling, hiring, design, and other

TABLE 1-2 Restrictions for Aircraft Classes Certified under 14 CFR Part 23

Restriction	Commuter	Normal	Utility	Aerobatic
Number of pilots	1 or 2	1	1	1
Max number of occupants	19	9	9	9
Max T-O weight	19,000 lb_f	12,500 lb_f	12,500 lb_f	12,500 lb_f
Aerobatics allowed?	No	No	Limited	Yes
Non-aerobatic operations permitted	Normal flying Stalls (no whip stalls) Steep turns ($\phi < 60°$)	Normal flying Stalls (no whip stalls) Lazy eights Chandelles Steep turns ($\phi < 60°$)	Normal flying Stalls (no whip stalls) Lazy eights Chandelles Steep turns ($\phi < 90°$) Spins (if approved)	N/A
Max maneuvering g-loading, n_+	$2.1 + \dfrac{24{,}000}{W + 10{,}000} < n_+ \leq 3.8$		4.4	6.0
Min maneuvering g-loading, n_-	$-0.4n_+ < n_- \leq -1.52$		-1.76	-3.0

W = maximum T-O weight. Maneuvering loads are based on 14 CFR 23.337.

A whip stall may occur when the airplane is stalled while in a slip. This can cause the outer wing to stall first and drop abruptly [5].

tasks, that many engineers consider less than glamorous. These people must be well-rounded in a number of disciplines: aerodynamics; performance analysis; stability and control; handling; power plants; weight analysis; structural layout; environmental restrictions; aviation regulations; history of aviation; and aircraft recognition, to name a few. Although not required to be an expert in any of these fields, their understanding must be deep enough to penetrate the surface. Knowing what to do, how to do it, and when to do it, is the key to a successful aircraft development program.

1.1.1 The Content of this Chapter

- **Section 1.2** presents a general description of the aircraft design process.
- **Section 1.3** presents two specific algorithms intended to guide the aircraft designer through the conceptual design process. If you are unsure of "what to do next," refer to these. They are based on actual industry experience and are not academic "cookbook" approaches.
- **Section 1.4** presents project management tools. Many beginning project leaders are often at a loss as to how to manage a project. If this is your predicament you need to study these tools. Project management revolves around knowing what to do and when to do it. Thus, the manager must construct a chronological order of the tasks that need to be completed.
- **Section 1.5** presents helpful approaches to describing engineering ideas using graphics ranging from three-view drawings to composite photo images. These are extremely helpful when trying to "sell" an idea.

1.1.2 Important Elements of a New Aircraft Design

Before going further, some specific topics must be brought up that the lead airplane designer must introduce and discuss thoroughly with the design team. Among those are:

Definition of the Mission

It is imperative that the mission of the new aircraft is very clearly defined. Is it primarily intended to serve as a cruiser? If so, what airspeed and cruising altitude is it most likely to see during its operation? Is it a cargo transport aircraft? How much weight must it carry? How fast, far, and high shall it fly? Is it a fighter? What energy state or loitering capabilities are required? The mission must be clearly defined because the airplane will be sized to meet that particular mission. An aircraft designed in this fashion will be most efficient when performing that mission. Clarity of this nature also has an unexpected redeeming power for the designer: It is very common during the development of aircraft that modifications to capabilities are suggested by outside agencies. In spite of being well meant, some such suggestions are often detrimental to the mission. A clearly defined mission allows the designer to turn down a disadvantageous suggestion on the basis that it compromises the primary mission.

Performance Requirements and Sensitivity

Performance requirements must be clearly defined and are usually a part of the mission definition. It is imperative to quantify characteristics such as the take-off distance, time to cruise altitude, cruise range, and even environmental noise for some types of aircraft. But it is also important to understand how deviations from the design conditions affect the performance. This is referred to as *performance sensitivity*. How does high altitude and a hot day affect the take-off distance? How about the upward slope of the runway? How does having to cruise, say, some 5000 ft below the design altitude affect the range? How about if the airplane is designed for a cruising speed higher than would be permitted by air traffic considerations and, therefore, is consistently operated at a lower cruising speed? How will that affect the range? Clearly, there are many angles to designing an aircraft, but rather than regarding it as a nuisance the designer should turn it into strength by making people in management and marketing aware of the deficiencies. And who knows – perhaps the new aircraft is less sensitive than the competition and this could be turned into a marketing advantage.

Handling Requirements (Stability and Control)

How important is the handling of the aircraft? Is this a small aircraft that is operated manually, rendering stick forces and responsiveness imperative? Is it a heavy aircraft with hydraulic or electric actuators, so stick forces are fed back to the pilot electronically and, thus, can be adjusted to be whatever is considered good? How about unsuspected responses to, say, thrust forces?

The Lockheed SA-3 Viking, an anti-submarine warfare aircraft, features a high wing with two powerful turbofan engines mounted on pylons. When spooling up, the aircraft experiences a powerful nose pitch-up tendency that is captured by a stability augmentation system (SAS) that was not originally designed into the prototype. The Boeing B-52 Stratofortress uses spoilers for banking. When banking hard, the spoiler on the down-moving wing is deployed and this reduces lift on the outboard part of that wing. This, in turn, means the center of lift moves forward, causing a nose pitch-up tendency, which the pilot must react to by pushing the yoke forward (for nose pitch-down). Handling issues of this nature must be anticipated and their severity resolved.

Ease of Manufacturing

Is it imperative that the aircraft will be easy to manufacture? Ease of manufacture will have a profound impact on the engineering of the product and its cost to the customer. A straight constant-chord wing can be manufactured at a lower cost than one that has tapered planform and compound surfaces, but it will be less efficient aerodynamically. Which is more important? The designer must have means to demonstrate why a particular geometry or raw material is required for the project. The concept of ease of marketing always looks good on paper, but this does not guarantee its success. For instance, it is simple to select composites for a new aircraft design on the grounds that this will make it easier to manufacture compound surfaces. But are they really needed? For some aircraft, the answer is a resounding *yes*, but for others the answer is simply *no*.

As an example, consider the de Havilland of Canada DHC-2 Beaver (see Figure 1-2). Designing this otherwise sturdy airplane from composites would be an unwise economic proposition. In the current environment it would simply be more expensive to build using composites and sell at the same or lower price than the aluminum version. To begin with, it is not easy to justify the manufacturing of an aerodynamically inefficient frustum-style fuselage[1] and constant-chord wing featuring a non-laminar flow airfoil with composites. Composites are primarily justifiable when compound surfaces or laminar flow wings must be manufactured. They require expensive molds to be built and maintained, and, if the aircraft ends up being produced in large numbers, the molds have to be manufactured as well; each may only last for perhaps 30–50 units.

The interested reader is encouraged to jump to Section 2.2, *Estimating project development costs*, for further information about manufacturing costs (in particular see Example 2-3, which compares development and manufacturing costs for a composite and aluminum aircraft). Cost analysis methods, such as the widely used DAPCA-IV, predict man-hours for the engineering development of composite aircraft to be around two times greater than that of comparable aluminum aircraft. They also predict tooling hours to double and manufacturing hours to be 25% greater than for aluminum aircraft. Labor and material are required not only to manufacture the airplane, but also to manufacture and maintain expensive tooling. As a result, composite aircraft are more expensive to manufacture in spite of substantial reduction in part count.

FIGURE 1-2 The de Havilland of Canada DHC-2 Beaver. *(Photo from Wikipedia Commons)*

This inflicts an important and serious constraint on the scope of production. Composites require heating rooms to ensure the resin cures properly so it can provide maximum strength. Additionally, vacuum bagging or autoclaves are often required[2] to force tiny air bubbles out of the resin during cure to guarantee that the certified strength is achieved. The manufacturer must demonstrate to the authorities that material strength is maintained by a constant production of coupons for strength testing. Special provisions must be made to keep down moisture and prevent dust from entering the production area, not to mention supply protective clothing and respirators to all technicians who work with the material. All of this adds more cost and constraints to the production and all of it could have been avoided if the designer had realized that requiring composites was more a marketing ploy than a necessity. This is not to say that composites do not have their place – they certainly do – but just because composites are right for one application, does not mean they are appropriate for another one.

Certifiability

Will the aircraft be certified? If the answer is yes, then the designer must explore all the stipulations this is likely to inflict. If no, the designer bears a moral obligation to ensure the airplane is as safe to operate as possible. Since non-certified airplanes are destined to be small, this can be accomplished by designing it to prevailing certification standards, for instance, something like 14 CFR Part 23 or ASTM F2245 (LSA aircraft).

Regulations often get a bad rap through demagoguery by politicians and ideologues, most of whom

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[1] A frustum-style fuselage is a tapered structure that does not feature compound surfaces. It is discussed in Chapter 12, *The Anatomy of the Fuselage*.

[2] Note that some manufacturers of composite structures claim that curing composites using vacuum "bagging" is equally effective as using an autoclave – it is certainly more economical. For instance see: http://www.gmtcomposites.com/why/autoclave.

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