Aircraft Design: Synthesis and Analysis

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Aircraft Design: Synthesis and Analysis
Preface

About AA241

This material is based on course notes for the class AA241A and B, a graduate level course in aircraft design at Stanford University. The course involves individual aircraft design projects with problem sets and lectures devoted to various aspects of the design and analysis of a complete aerospace system. Students select a particular type of aircraft to be designed and, in two academic quarters, define the configuration using methods similar to those used in the aircraft industry for preliminary design work. Together with the vehicle definition and analysis, basic principles of applied aerodynamics, structures, controls, and system integration, applicable to many types of aerospace problems are discussed. The objective of the course is to present the fundamental elements of these topics, showing how they are applied in a practical design.

About the Web Version of These Notes

This internet-based version of Aircraft Design: Synthesis and Analysis is an experiment. It is the forerunner of a new type of textbook whose pages may be distributed throughout the world and accessible via the world-wide-web. The text will be evolving over the next few months; new items will be added continually.

This may turn out to be a true "Hitchhiker's Guide To Aircraft Design" if people are interested in contributing. You are welcome to send revisions, suggestions, pictures, or complete sections. I will review them and consider including them (with credits) where appropriate. Send submissions (in html, gif, or jpeg form) to Ilan Kroo.

Why a Digital Textbook?

There are several reasons for using this format for the course notes:

- They are easily updated and changed -- important for aircraft design so that new examples and methods can be added.
- Analysis routines can be built into the notes directly. The book permits you to build up a design as you progress through the chapters.
- The format permits easy access to information and organizes it in a way that cannot be done in hardcopy.
- It is inexpensive to include color pictures and video.
It is possible, by providing just a couple of custom pages, to tailor the textbook for a particular course. If the material on supersonic flow is not appropriate for the class, a new outline and contents page may be created that avoids reference to that material.

About the Authors

Ilan Kroo is a Professor of Aeronautics and Astronautics at Stanford University. He received a degree in Physics from Stanford in 1978, then continued graduate studies in Aeronautics, leading to a Ph.D. degree in 1983. He worked in the Advanced Aerodynamic Concepts Branch at NASA's Ames Research Center then returned to Stanford as a member of the Aero/Astro faculty. Prof. Kroo's research in aerodynamics and aircraft design has focussed on the study of innovative airplane concepts and multidisciplinary optimization. He has participated in the design of high altitude aircraft, human-powered airplanes, America's Cup sailboats, and high-speed research aircraft. He was one of the principal designers of the SWIFT, tailless sailplane design and has worked with the Advanced Research Projects Agency on high altitude long endurance aircraft. He directs a research group at Stanford consisting of about ten Ph.D. students and teaches aircraft design and applied aerodynamics at the graduate level. In addition to his research and teaching interests, Prof. Kroo is president of Desktop Aeronautics, Inc. and is an advanced-rated hang glider pilot.

Richard Shevell was the original author of several of these chapters. He worked in aerodynamics and design at Douglas Aircraft Company for 30 years, was head of advanced design during the development of the DC-9 and DC-10, and taught at Stanford University after that for 20 years. To a large extent, this is his course.
Instructions

This version of Aircraft Design: Synthesis and Analysis is intended for use with Netscape Navigator, version 4.0 or later, or with Microsoft's Internet Explorer, version 4.0 or later. The text makes use of frames, javascript, and Java, so be sure your browser supports this and that these features are enabled. Please see the help available from Netscape or Microsoft for using the browser software.

Navigating

To navigate through this text, click on the topic shown in the frame to the right. The browser remembers where you have been, and sections that you have already visited are displayed in another color. To reset the history information so that all section names are displayed in the default color, follow the browser instructions on clearing the history or disk cache.

We have minimized the use of embedded hypertext links as we have found this often confuses students trying to navigate through a textbook. It also makes it difficult to expand or delete sections to form a custom version of the text (see below). This means that most of the navigation is done through the table of contents. A rather complete table of contents can also be found in the prefatory information and active links on this page will also work. Some hypertext links are used, but most are restricted to single level pages with additional detail, as might be found in an extended footnote.

Printing

Most pages in the text can be printed directly from the browser. Make sure to specify color or greyscale printing for improved photo images. The chapter and section numbers are generated by javascript on the fly, and some browsers will omit the numbers from the printed heading name. Also, at the time of this release, no platform-independent printing strategy is available for java applets. To print the results from one of the interactive computations, you may need to capture the screen image and send it to the printer. This can be done on most platforms, but the approach depends on the operating system.

Frames

If you are confused by navigating with frames, please read the material available from the Netscape or Microsoft sites and be patient. Many people do not like frame-based pages, but after years of experimentation, we have found that this really does seem to work best for this text. Let us know if you have other ideas.

You may resize the frames to make more or less of the table of contents visible. The best size depends on
the size of your monitor and your personal preferences -- experiment. Also, because you may want to make as much of the content visible in the available screen space, we recommend that you hide some of the toolbar or directory areas at the top of the screen. You can do this from the browser preferences or options menus.

**Trouble-Shooting**

If you have other difficulties, please check the Desktop Aeronautics web site: http://www.desktopaero.com for further suggestions and any fixes that may be posted.
General References


Articles in *Aviation Week & Space Technology*, McGraw-Hill.


*Aircraft Design Information Sources* by W.H. Mason at VPI is an excellent annotated bibliography on many aspects of aircraft design and is available on the web.
Introduction

This chapter includes a discussion of the history of aircraft development, some notes on aircraft origins (how a new aircraft comes to be developed), a few ideas on future aircraft types and technology, and a number of references and links to related sites.

- **Historical Notes**
- **Aircraft Origins**
- **Future Aircraft**
- **References**
History of Transport Aircraft and Technology

There are numerous interesting books on the history of aircraft development. This section contains a few additional notes relating especially to the history of aircraft aerodynamics along with links to several excellent web sites. Among the conventional references of interest are the history section in Shevell's Fundamentals of Flight and John Anderson's book on the history of aerodynamics (see References).

Here are some additional links with aeronautical history.

- Some historical notes on the history of aircraft and aerodynamics.
- Boeing History
- Airbus History
- Milestones in the History of Flight (Air and Space Museum)
- Invention of the Airplane
- The Octave Chanute Pages
- AIAA 1903 Wright Flyer Project
- The Wright Brothers
References

History

General History:


Early Development:


Aircraft Origins


Related Web Sites

British Airways overview of the airline industry
Historical Notes

It was not long ago that people could only dream of being able to fly.

The dream was the subject of great myths and stories such as that of Icarus and his father Daedalus and their escape from King Minos' prison on Crete. Legend has it that they had difficulty with structural materials rather than aerodynamics.

A few giant leaps were made, with little forward progress. Legends of people attempting flight are numerous, and it appears that people have been experimenting with aerodynamics for thousands of years. Octave Chanute, quoting from an 1880's book, La Navigation Aerienne, describes how Simon the Magician in about 67 A.D. undertook to rise toward heaven like a bird. "The people assembled to view so extraordinary a phenomenon and Simon rose into the air through the assistance of the demons in the presence of an enormous crowd. But that St. Peter, having offered up a prayer, the action of the demons ceased..."

In medieval times further work in applied aerodynamics and flight were made. Some rather notable people climbed to the top of convenient places with intent to commit aviation.

Natural selection and survival of the fittest worked very effectively in preventing the evolution of human flight.
As people started to look before leaping, several theories of flight were propounded (e.g. Newton) and arguments were made on the impossibility of flight. This was not a research topic taken seriously until the very late 1800's. And it was regarded as an important paradox that birds could so easily accomplish this feat that eluded people's understanding. Octave Chanute, in 1891 wrote, "Science has been awaiting the great physicist, who, like Galileo or Newton, should bring order out of chaos in aerodynamics, and reduce its many anomalies to the rule of harmonious law."

Papers suggested that perhaps birds and insects used some "vital force" which enabled them to fly and which could not be duplicated by an inanimate object. Technical meetings were held in the 1890's. The ability of birds to glide without noticeable motion of the wings and with little or negative altitude loss was a mystery for some time. The theory of aspiration was developed; birds were in some way able to convert the energy in small scale turbulence into useful work. Later this theory fell out of favor and the birds' ability attributed more to proficient seeking of updrafts. (Recently, however, there has been some discussion about whether birds are in fact able to make some use of energy in small scale air motion.)

The figure here is reproduced from the 1893 book, First International Conference on Aerial Navigation. The paper is called, "The Mechanics of Flight and Aspiration," by A.M. Wellington. The figure shows the flight path of a bird climbing without flapping its wings. Today we know that the bird is circling in rising current of warm air (a thermal).
Designs were made before people had the vaguest idea about how aircraft flew. Leonardo Di Vinci designed ornithopters in the late 1400's, modeled on his observations of birds. But apart from his work, most designs were pure fantasy.

The first successes came with gliders. Sir George Cayley wrote a book entitled "On Aerial Navigation" in 1809. He made the first successful glider in 1804 and a full-size version five years later at the age of 36. For many years thereafter, though, aeronautics was not taken seriously, except by a small group of zealots. One of these was William Henson who patented the Aerial Steam Carriage, shown here, in 1842. The aircraft was never built, but was very well publicized (with the idea of raising venture capital). Both the design and the funding scheme were ahead of their time.
Some rather ambitious designs were actually built. The enormous aeroplane built in 1894 by Sir Hiram Maxim and shown below, weighed 7,000 lbs (3,200 kg) and spanned over 100 ft (30 m).

In Germany in the 1860's Otto Lilienthal took a more conscientious approach with tests on a whirling arm, ornithopter tests suspended from a barn, and finally flight tests of a glider design. He studied the effect of airfoil shape, control surfaces, propulsion systems, and made detailed measurements of bird flight. His book, "Birdflight as the Basis of Aviation" was an important influence on later pioneers.
This was one of Lilienthal's last flights. He was killed in 1896 by a gust-induced stall too near the ground.

From Lilienthal's first flights in the 1890's, to the Wright brother's glider flights and powered aircraft, evolution was quick.
Orville Wright soars a glider in 50 mi/hr (80 km/hr) winds for 10 minutes at Kitty Hawk, Oct. 24, 1911. This was one of the first applications of a aft horizontal tail on the Wright aircraft. From Aero Club of America Bulletin, Jan. 1912.

The first 'Aerial Limousine', 1911. "The limousine has doors with mica windows and seats for four persons fitted with pneumatic cushions, the pilot seats in front. A number of flights have been made, with and without passengers, with entire success."
It is truly amazing how quickly this has happened: we tend to think of the dawn of flight as something from Greek mythology, but it has been only about 100 years since people first flew airplanes.

Of course other things happen quickly too. When the 747 was designed calculators were big whirring contraptions which sat on desks and could not do square roots. The earlier transports, still flying today, were designed when calculators were women who worked the computing machines.

The picture below shows the computational grid for a modern calculation of the flow over 737 wing with flaps and slats deployed.

The revolution in computing has changed the way we do computational applied aerodynamics, but we still utilize a variety of methods. Computation, ground-based testing, and finally, flight tests.
The plot shows the computer power required to perform the indicated calculations in about 15 minutes using 1985 algorithms. Using more modern supercomputers and now, parallel machines, this time is dropping dramatically. Yet, we are still a long way from routine applications of direct Navier-Stokes simulations or LES.
The Cray C916 Supercomputer

Projects such as NASA's Numerical Aerodynamic Simulation program continue to develop simulation software that takes advantage of recent advances in computer hardware and software.

In this class we will talk about the methods used to compute aerodynamics flows. We will use simple methods on personal computers and design airfoil sections. We will analyze wings and talk about the elements of wing design. We will be talking about fundamental concepts that can be demonstrated with simple programs but which form the basis for modern computational methods. We will discuss how these methods work, what they can and cannot do. We will use results from analytical studies, wind tunnel tests, and CFD to discuss wing and airplane design.

While we discuss aircraft a great deal, the concepts and methods are relevant to a wide range of applications: Weather prediction, boat design, disk drive aerodynamics, architectural applications, and land-based vehicles.

The aerodynamics of bumble bees, disk heads, weather, and many other things is not a solved problem. While it is impressive that the methods in use today do so well, we are still not able to predict many flows.