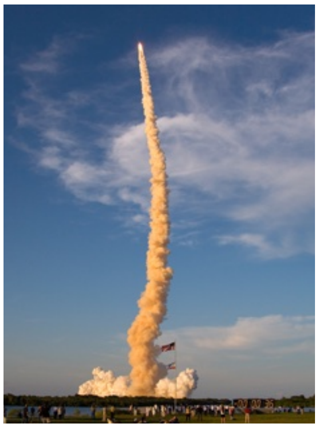
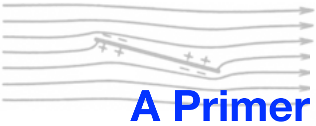
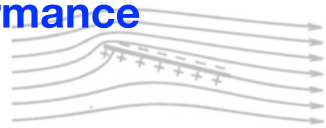
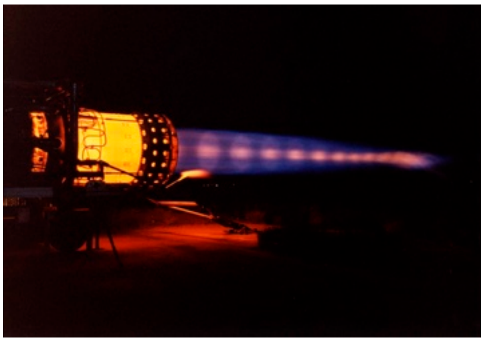




A Primer of Aeronautics and Aircraft Performance





(These notes are the basis of a freshman- and sophomore-level 1-semester introductory course. No prior knowledge of fluid mechanics is assumed.)

The purpose of this course is to:

1. serve as orientation guide to aerospace engineering;
2. provide historical context to current status of aerospace engineering;
3. introduce the concept of design engineering;
4. provide basic introductory material on fluid mechanics and aerodynamics;
5. explain the central features of the Earth's atmosphere and its approximate/engineering model;
6. explain the main sources of aircraft lift and drag and how they are related by flight conditions;
7. introduce the key aspects of propulsion systems for aerospace engineering;
8. **explain the study of aircraft performance as a topic in applied aerodynamics and mechanics;**
9. introduce the central operational concepts of aircraft stability, trim, and controllability.
10. introduce concepts of aircraft structures

Sources of material and figures

Various figures have been adopted or adapted from a variety of texts and internet sources.

Where possible, attribution has been made for figures that have been re-used.

The main texts from which material has been adopted are listed below.

- Anderson, *Aircraft Performance and Design*, McGraw-Hill (1990)
- Anderson, *Introduction to Flight*, McGraw-Hill (2008)
- Barnard & Philpott, *Aircraft Flight*, Longman (1989)
- Brandt, Stiles, Bertin & Whitford, *Introduction to Aeronautics*, AIAA (2004)
- Cutler & Liber, *Understanding Aircraft Structures*, Blackwell (2005)
- Drela, *Flight Vehicle Aerodynamics*, MIT Press (2014)
- Etkin & Reid, *Dynamics of Flight: Stability and Control*, Wiley (1986)
- Gunston, *Flight Handbook*, Iliffe (1962)
- Howe*, Aircraft Structures*, AIAA (2010)
- Jones, *Wing Theory*, Princeton (1990)
- Kermode, *Mechanics of Flight*, Prentice-Hall (2006)
- Kuethe & Chow, *Foundations of Aerodynamics*, Wiley (1996)
- Longhand, *Gliding, The British Gliding Association Manual*, Black (2002)
- McCormick, *Aerodynamics, Aeronautics and Flight Mechanics*, Wiley (1995)
- Nicolai, *Fundamentals of Aircraft Design*, METS Inc (1984)
- Prandtl & Tietjens, *Fundamentals of Hydro- and Aeromechanics*, Dover (1957)
- Raymer, *Aircraft Design: A Conceptual Approach*, AIAA (2006)
- Saarlas, *Aircraft Performance*, Wiley (2007)
- Shevell, *Fundamentals of Flight*, Prentice-Hall (1989)
- Simons, *Model Aircraft Aerodynamics*, Motorbooks Int (1983)
- Smits, *A Physical Introduction to Fluid Dynamics*, Wiley (2000)
- Stinton, *The Design of the Aeroplane*, Blackwell (1983)
- Tennekes, *The Simple Science of Flight*, MIT Press (2006)
- Torenbeek, *Synthesis of Subsonic Airplane Design*, Martinus Nijhoff (1982)
- Torenbeek & Wittenberg, *Flight Physics*, Springer (2009)
- Whitford, *Design for Air Combat*, Jane's (1989)
- Whitford, *Evolution of the Airliner*, Crowood (2007)
- White, *Fluid Mechanics*, McGraw-Hill (1986)

Central INTRODUCTORY themes of course

1. Fluid mechanics

1. Fluids (gases and liquids) vs solids
2. Units and dimensions, dimensionless numbers
3. Fluid and flow quantities: density, temperature, velocity, viscosity, pressure
4. Conservation of mass, momentum and energy
5. Forces and moments on solid bodies

2. Aerodynamics

1. Mechanisms of lift and drag production
2. Laminar and turbulent flow
3. Boundary layers and flow separation
4. Mechanics and performance of airfoils and wings
5. Lift vs drag polar diagram

3. Propulsion systems

1. Thrust generation and propulsive efficiency
2. Levels of integration of air-breathing engines
3. Power vs thrust
4. Effect of aircraft altitude and speed
5. Simplified performance models
6. Fuel energy capacity and thermal efficiency

4. (subsonic) Aircraft performance

1. Equations of motion for steady symmetric and turning flight
2. Whole-aircraft drag polar
3. Load factor and V–n diagram
4. **Steady level flight**: lift, weight, thrust (or power) and drag. Speeds for given thrust. Altitude effect on thrust required. Aircraft absolute ceiling. Speed/altitude envelope. Power in level flight. Range and endurance. Three ideal optimum speeds.
5. Gliding flight, Climbing flight, Turning flight
6. Takeoff and landing

5. Stability and control

1. Static and dynamic stability
2. Longitudinal static stability and trim
3. Longitudinal control authority

6. Compressible flow

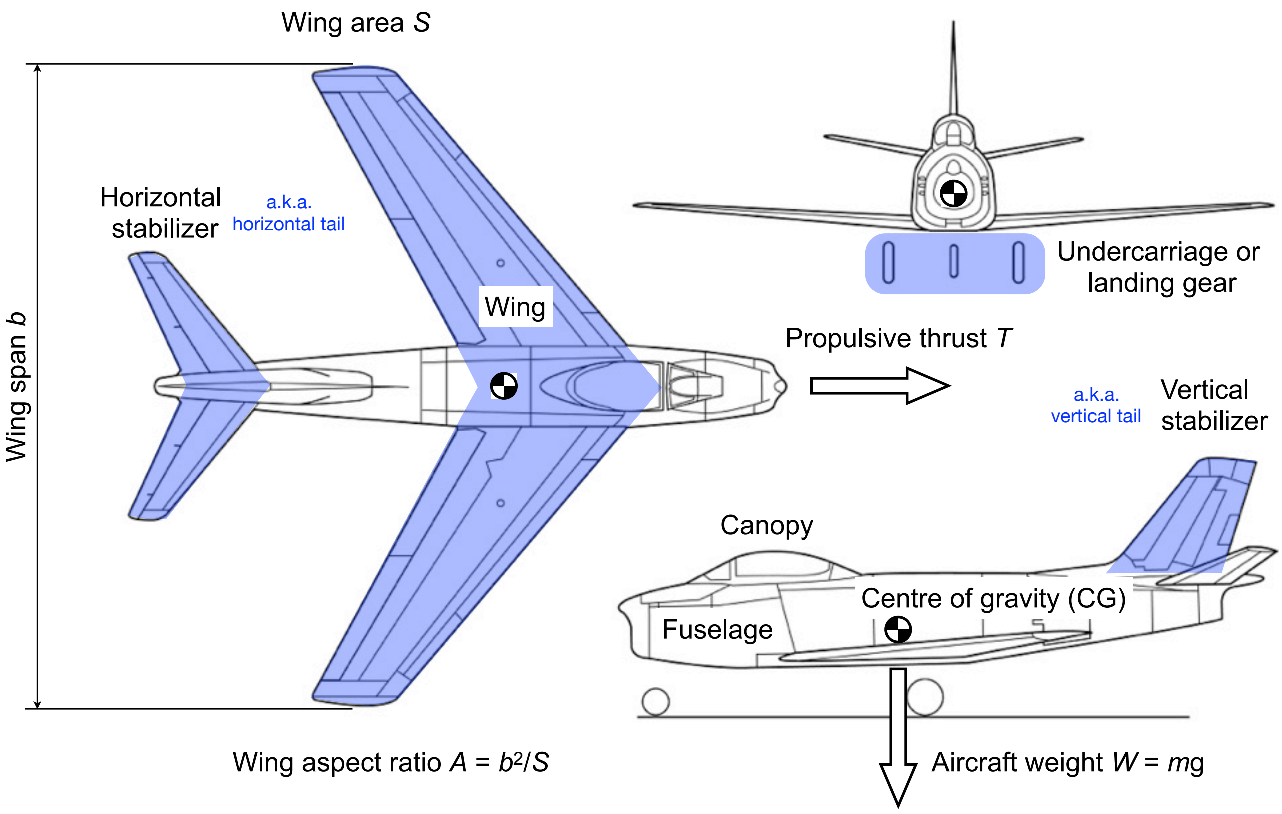
1. Normal and oblique shocks
2. Wing sweep

7. Aircraft structures

1. Review of structural types
2. Air and inertia/weight loads

Aircraft components and nomenclature

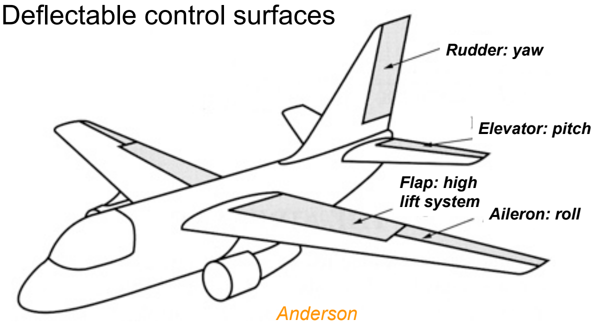
Standard aircraft components and quantities



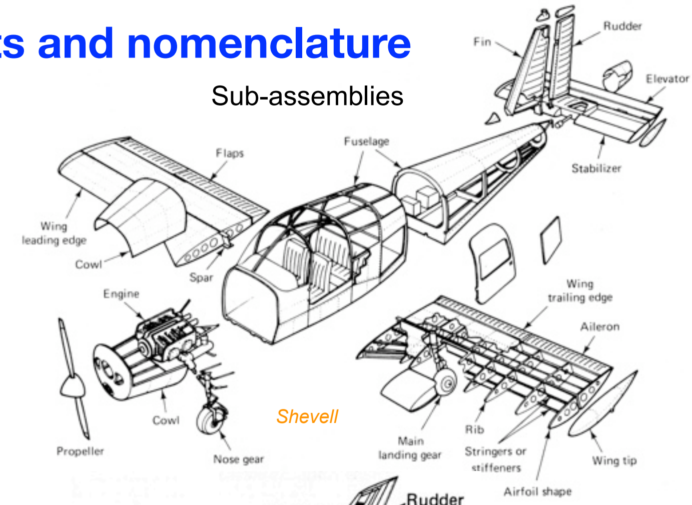
F-86 3-view from NASA

Aircraft components and nomenclature

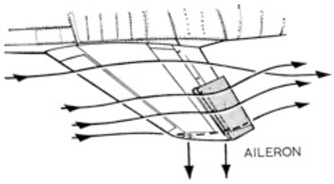
Deflectable control surfaces



Sub-assemblies



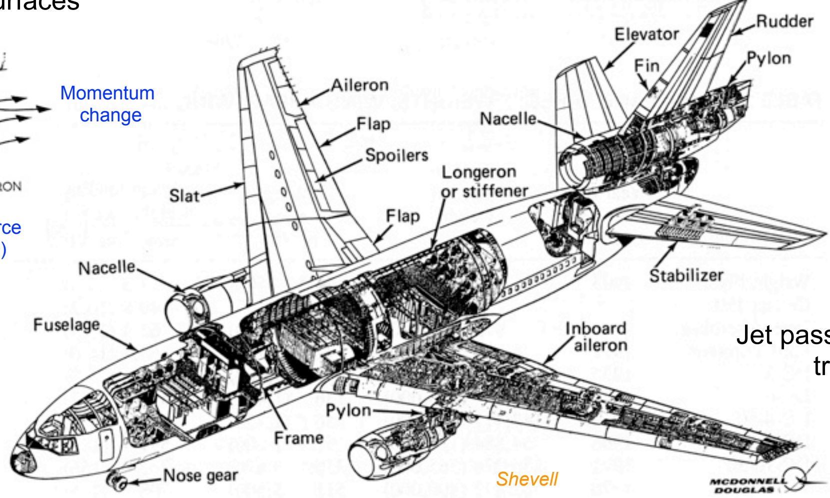
Principle of control surfaces



Momentum change

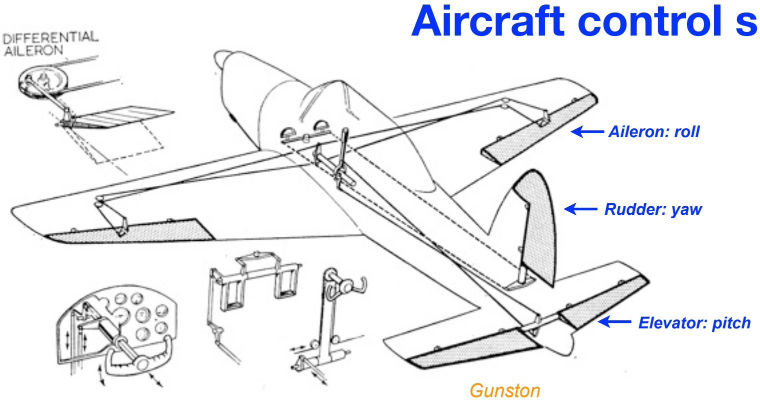
Produces additional force (+ moment about CG)

Gunston



Jet passenger + cargo transport.

Aircraft control surfaces

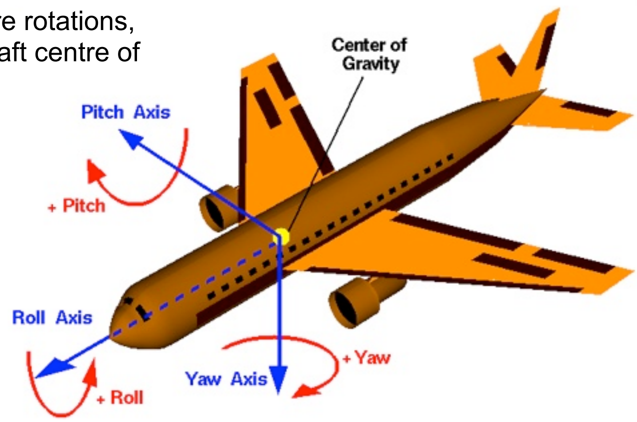


Gunston

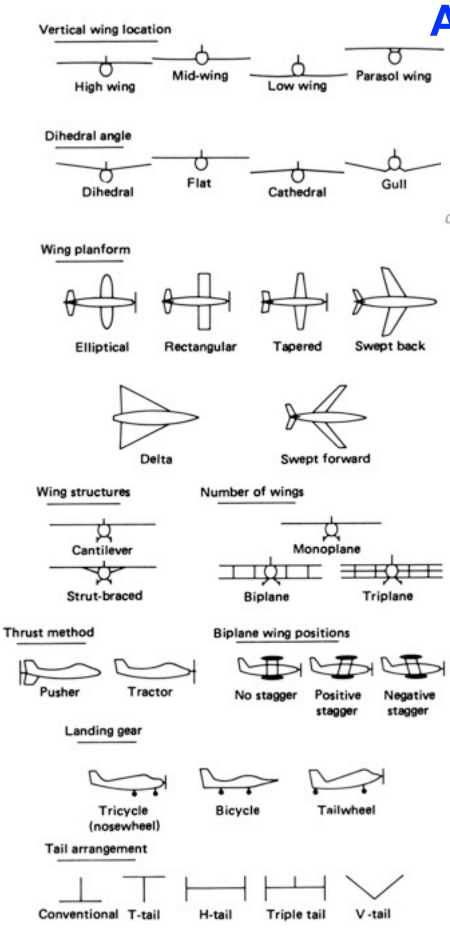
Aircraft control surfaces are by tradition mechanically linked to simple pilot-activated controls. More modern aircraft have similar controls but may have no direct linkages.

Pitch, yaw and roll are rotations, taken about the aircraft centre of gravity (CG).

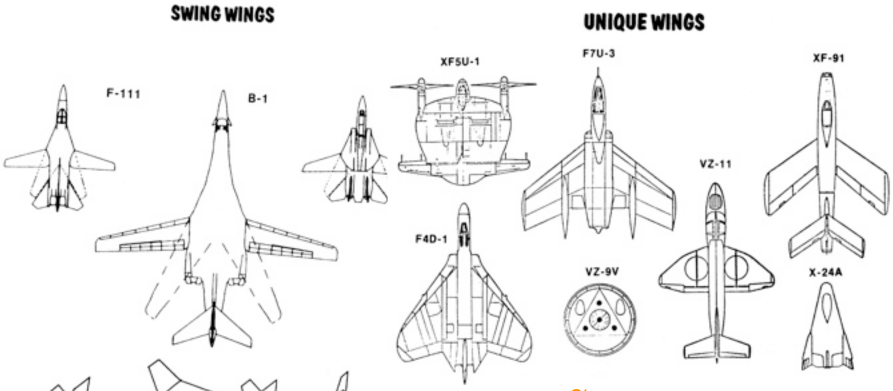
NASA



Aircraft layout options



Shevell



Chuprun

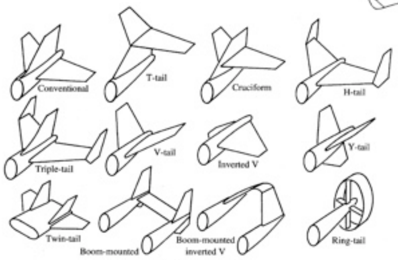


Fig. 4.30 Aft tail variations.

Raymer

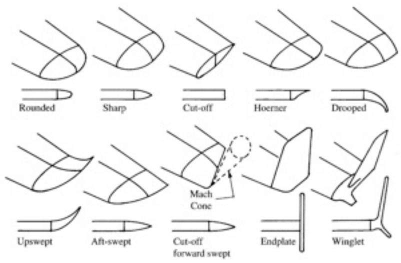


Fig. 4.29 Wing tips.

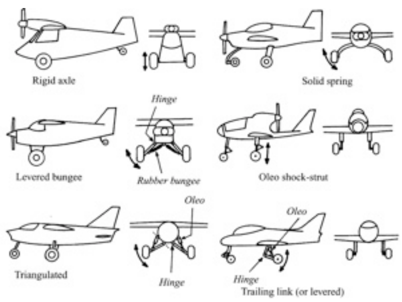


Fig. 11.9 Gear/shock arrangements.

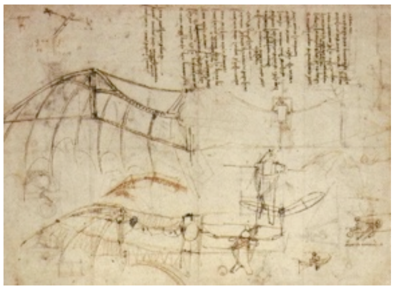
Raymer

Milestones in aerospace engineering

Reading:

Torenbeek & Wittenberg: Ch 1
Brandt et al.: Ch 1 (section 1.5)

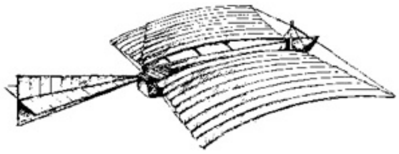
1505: Leonardo da Vinci: concepts for heavier-than-air flight machines, helicopter



1783: Montgolfier: hot-air balloon flights

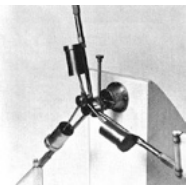
1852: Giffard: first powered cross-country balloon flight

1852: Cayley: model aircraft, glider and concept of lift and drag



Cayley's design of an aircraft (1799) conforming to the modern concept of configuration: (1) Fixed wings for lift, (2) movable tail for control, and (3) rows of "flappers" beneath the wings for thrust

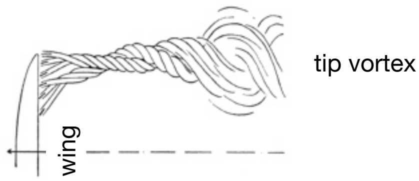
1890: Hargrave: box-girder wire-brace biplane wing, rotary engine concept



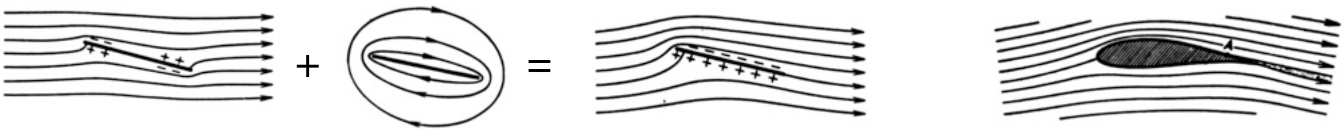
1893: Lilienthal: hang glider and aerodynamic experiments

INTRODUCTION

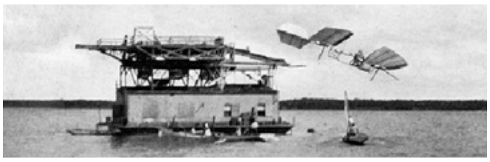
1884: Lanchester: lift and circulation/swirl for finite wings



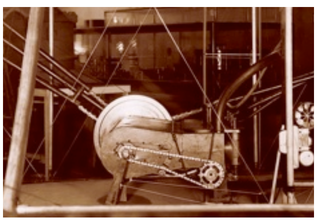
1902: Kutta/Joukowski: resolved ideal frictionless flow theory to production of lift for infinite wings

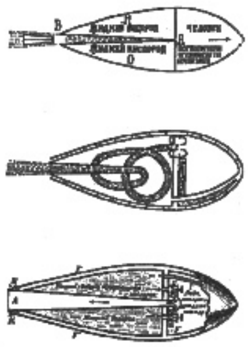


1903: Langley and others: unsuccessful powered aircraft



1903: Wright brothers: first successful powered aircraft & aero engine



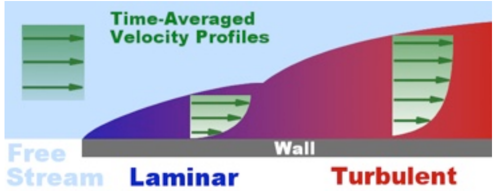


Tsiolkovsky Rocket Designs

1903: Tsiolkovsky: ideal rocket equation, science of space flight

INTRODUCTION

1904: Prandtl: boundary-layer theory



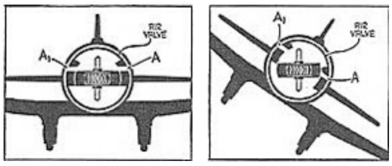
1907: Cornu: untethered helicopter flight

1909: Bleriot: cross-Channel flight

1909: Wilm: duralumin, first aircraft-specific alloy (aluminium & copper)

1912: Bechereau: stressed-skin construction

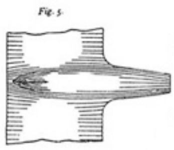
1912: Sperry: autopilot



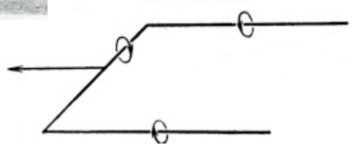
INTRODUCTION

1914–18: First World War: dominance of wood+wire aircraft as weapons

1915: Junkers: superiority of thick airfoils, all-metal monoplane, flying wing concept

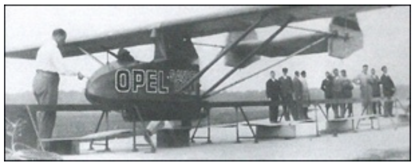


1918: Prandtl: mathematical formulation of Lanchester's lifting-line concept for finite wings



1926: Goddard: liquid-fueled rocket model

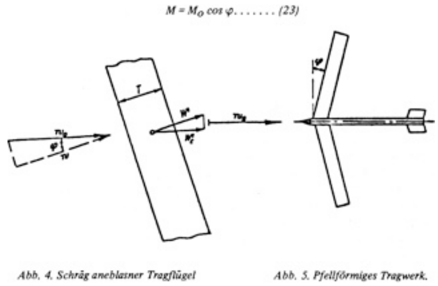
1927: Lindberg: solo New York–Paris flight



1929: Opel: first rocket-powered aircraft

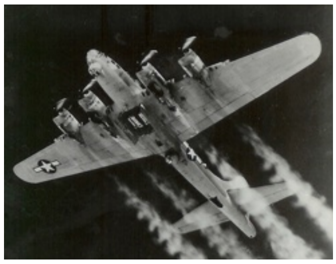
1933–35: Boeing/Douglas: first modern airliners

1935: Busemann: swept wing concept for transonic drag reduction



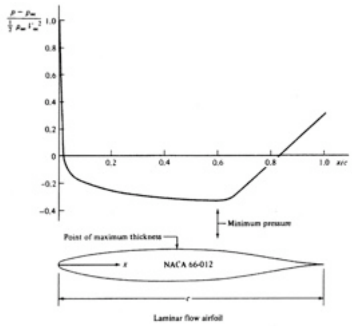
1936: Boeing: airliner with pressurized cabin

1939: Obain: first gas-turbine powered aircraft



1939–45: Second World War: apogee of metal-skinned piston-engined aircraft as weapons

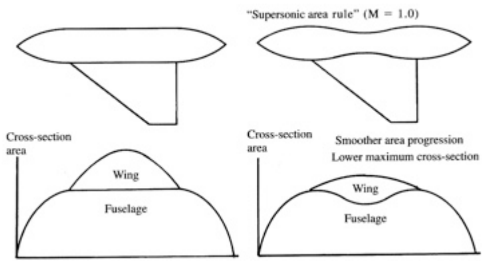
1940: de Havilland: sandwich panel skin/structure (wooden)



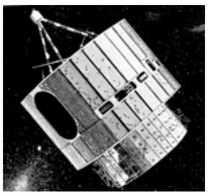
1940: NACA: laminar boundary layer airfoil design

1942: von Braun: A4/V2 intercontinental ballistic missile, inertial guidance system

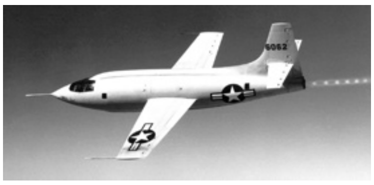
1943: Frenzel: area-rule concept for transonic drag reduction



1945: Clarke: concept of geostationary satellite



1947: NACA: Mach 1.06 in level flight: X-1



1949: de Havilland: first jet airliner

1950–53: Korean War: jet engined combat aircraft come of age as weapons

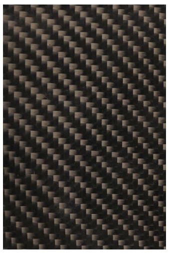
1951: NACA: X-5 variable-sweep research aircraft

1954: Boeing/Douglas: commercially successful jet airliners

1957: Sputnik: first Earth satellite

Sergey Korolev, chief designer

1958: Union Carbide: carbon fibre

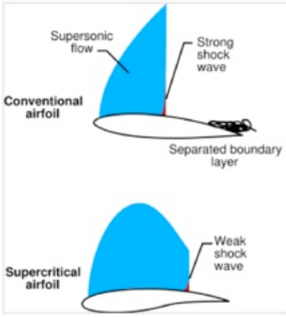


1959: NASA: X-15 hypersonic research aircraft

1959-75: Vietnam war: ground-air missile and helicopter come of age as weapons

1961: Vostok 1: Yuri Gagarin first man in space

1965: NASA: Supercritical airfoil design for transonic drag minimization



1969: Aerospatiale-BAC: Concorde supersonic passenger transport

INTRODUCTION

1969: NASA: Neil Armstrong walks on the moon

1970: Boeing: Wide-body jet passenger transport

1979: McCready: first successful man-powered aircraft

1979: Lockheed: first specifically-designed stealth aircraft

1981: NASA: Space shuttle

1989: GPS released for civilian use

2000: Autonomous aircraft

2013: Composite-structure airliner

Introduction to aerospace design concepts

21

Analysis vs design

Very broadly stated:

Analysis: given something specific, work out how it performs under a given set of inputs.

Design: given a set of inputs and a required performance, work out something specific to do the job.

When stated this way one can see that design is the inverse of analysis.

For example, consider Newton's 2nd Law expressed as $F = ma$.

A simple problem for analysis might be: given m and a, what is the value of F?

In which case we'd use the equation as stated: $F = ma$.

A problem of design might be: given a certain amount of force F and a required value of a, what must be the value of m?

In this case we'd invert the equation to give $m = a/F$.

This helps make the point that design and analysis use the same sets of equations, but they are considered in different ways, and one is the inverse of the other.

We first need analysis (typically based on some form of mechanics, e.g. solid mechanics, fluid mechanics, thermodynamics...) in order to get the equations which are needed – these are required before engineering design can be carried out.

Essentially this is the key distinction between science and engineering: scientists carry out analysis, while engineers carry out design (among other things), having first mastered analysis.

22

Analysis vs design

Engineering courses teach a great deal of analysis mainly because

1. It has to be understood first, before inversion can be carried out;
2. It is easier, in general;
3. Analysis typically has one right answer while in design there may be many – or none!

Aerospace design is somewhat complicated because

1. The analysis may be demanding;
2. Vehicle performance depends strongly on weight, which is difficult to estimate in advance.

On the other hand the range of tasks to be performed is not very large, and there is a comparatively small set of key design variables which are shared among all aircraft designs.

Examples of aircraft performance requirement variables

Maximum payload weight	W_p
Maximum range	R
Cruise speed and altitude	V_c, h
Landing approach speed	V_{app}

Examples of aircraft design variables

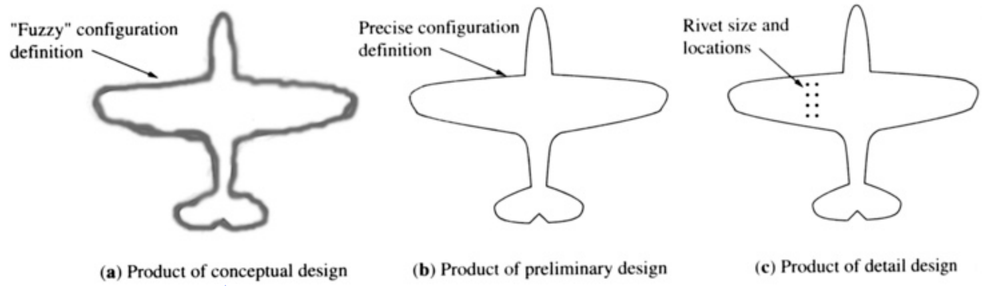
Maximum take-off weight	W_0
Wing area	S
Maximum engine sea-level thrust	T_{SL}
Aerodynamic parameters e.g.	$C_{L\max}$

As a result there is a fairly well-developed design methodology and a comparatively small set of design categories (e.g. general aviation, regional propellor transport, economy passenger jets).

Part of the purpose of this subject is to provide background to both analysis and design in aerospace engineering.

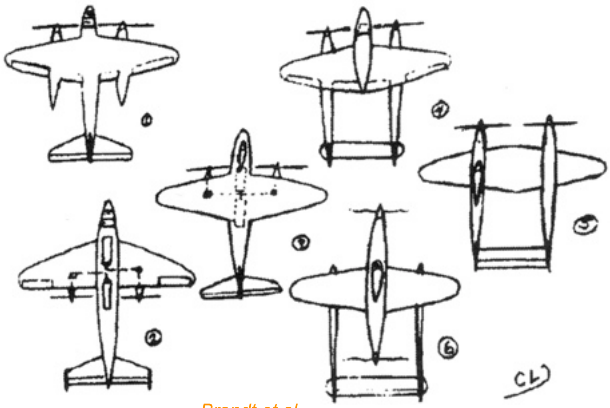
Design phases: configuration choices

Design phases



Anderson

Lockheed design team alternative configuration sketches for the P38 Lightning , and the finished product.

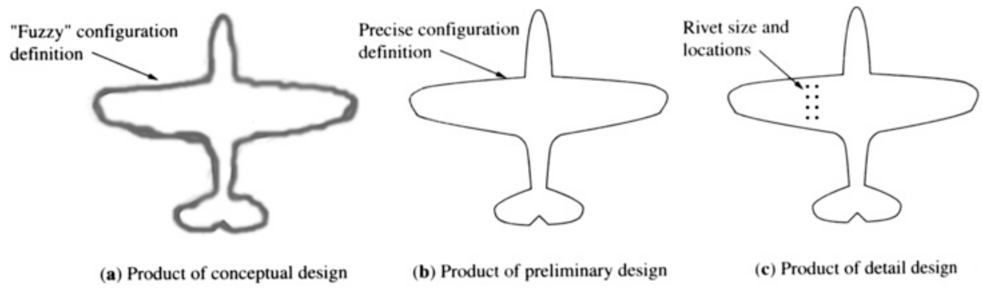


Brandt et al.

NASA

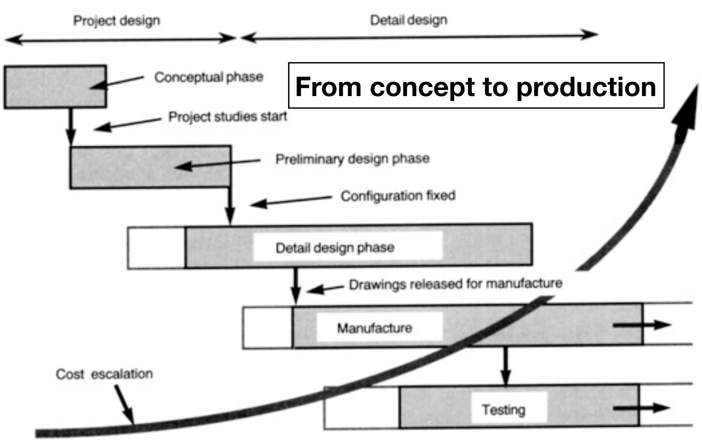
Design phases: iteration

Design phases



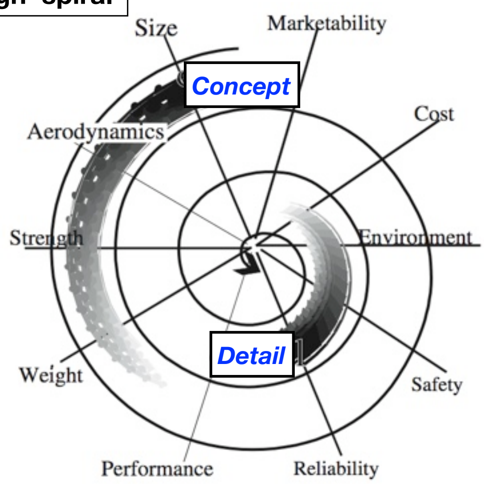
Anderson

From concept to production



Jones?

Design 'spiral'

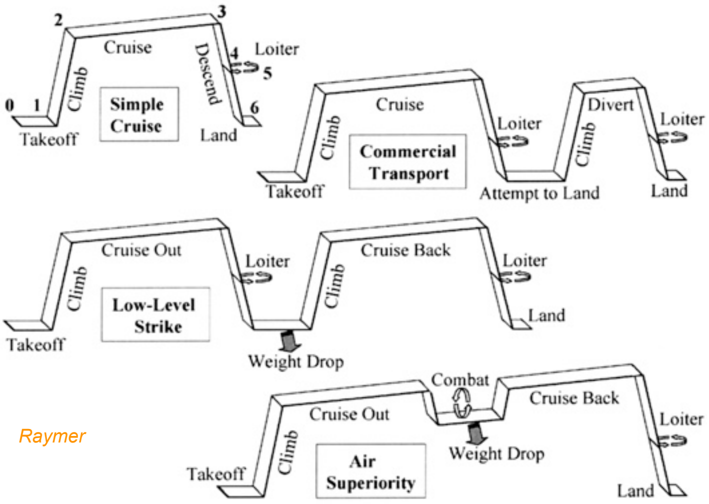


Tools for conceptual design

The idea of 'mission profile' that outlines speed and height as a function of time is very commonly used as an aid to conceptual design.

This is used to help estimate fuel use, a very significant part of aircraft weight.

The mission profile is usually specified at the start of the design process.



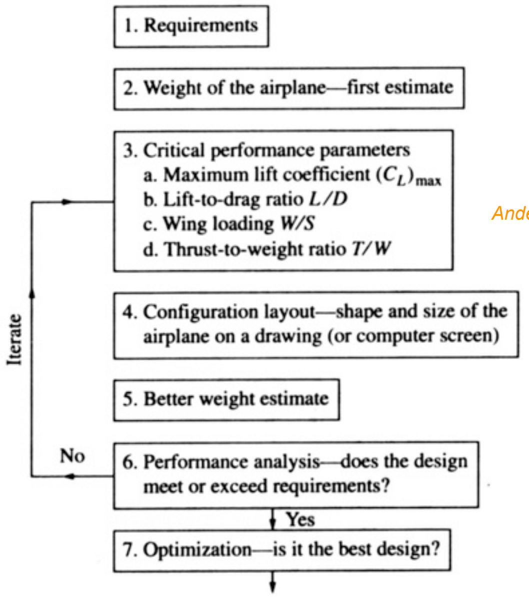
Raymer

Fig. 3.2 Typical mission profiles for sizing.

Conceptual design phase of a new aircraft involves estimating key design variables:

Weight W
Wing area S
Engine thrust T
Aerodynamic parameters e.g. $C_{L\max}$

The Seven Intellectual Pivot Points for Conceptual Design



Anderson

Design categories and correlations

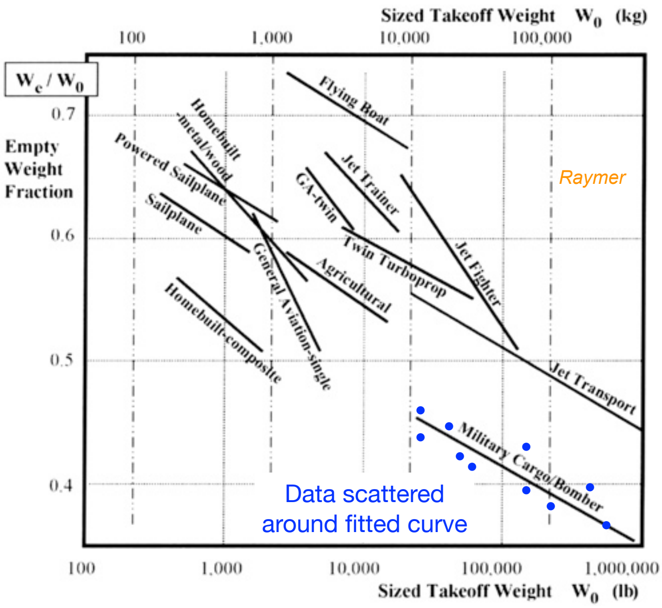
Statistical information based on analysis of previous designs within categories is very often used as an aid to aircraft preliminary design.

This applies especially to preliminary weight estimation.

Typical aircraft categories:

1. Homebuilts
2. Single-engine propeller-driven aircraft
3. Twin-engine propeller-driven aircraft
4. Agricultural aircraft
5. Business jets
6. Regional turbopropeller-driven aircraft
7. Jet transports
8. Military trainers
9. Fighters
10. Military transport, patrol, bomber aircraft
11. Flying boats, amphibious and float aircraft
12. Supersonic cruise aircraft

E.g. it is found that within categories, the empty weight (or mass) fraction W_e/W_0 correlates with the maximum takeoff weight W_0.



Raymer

A curve fit (correlation) commonly employed is

$$W_e/W_0 = c\,W_0^b$$

This kind of approach is less helpful when a radically new design is needed, e.g. for a completely new aircraft category.