AE 429 – Performance and Flight Mechanics

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Detailed Outline

Four Historical Periods of Airplane Design

1. Pre-Wright Era
2. Strut-and-Wire Biplanes
3. Mature Propeller-driven Airplanes
4. Jet-propelled Airplanes

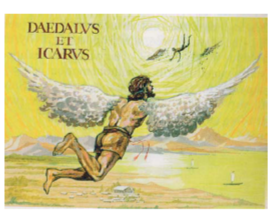
Good airplane design requires a knowledge of previous design

- understand trends
- identify areas in need of technological advancement
- evolutionary vs. revolutionary

"Tower Jumpers"

People attempting to fly by means of wings strapped to their arms and/or legs

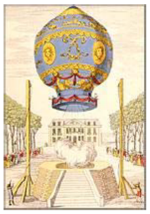
The myth of Daedalus and Icarus, on of the earliest recorded accounts of man's attempt to fly, illustrates the concept of "tower jumpers".



First Manned Aircraft

Around 1299 A.D, Marco Polo claimed to see Chinese sailors attached to kites being used as military observers. This could be considered the first manned aircraft.

But…the first true POWERED flight with humans on board, was in a hot air balloon. This occurred in France in 1783. The Montgolfier Brothers created a balloon that was piloted by two others.

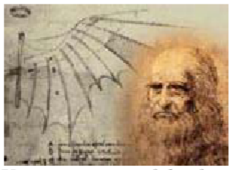


unmanned balloon

manned balloon

Ornithopters

The flapping of wings to generate lift, powered by mechanical devices.



da Vinci was one of the first to propose ornithopters in the 1400s

Robert Frost Attempt, 1904

Aerovironment's Microbat

Kiselev's Proposed Ornithopter

DeLaurier's C-GPTR

Why Don't Ornithopters Work?

Manned ornithopters have little chance of success because humans cannot match the remarkable physiological capabilities of birds.

Energy output of birds:

800 heart beats per minute by a sparrow
400 per minute respiration rate of a pigeon in flight

The Modern Airplane Configuration

Sir George Cayley first pioneered the concept for the modern airplane configuration in 1799

- fixed wings, tail, fuselage

- separate mechanism for propulsion
"seperation of lift and propulsion"

- recognized that the function of thrust ws to overcome aerodynamic drag

- drew the first lift-drag vector diagram in the history of aeronautical engineering

Sir George Cayley

Silver disk inscribed by Cayley showing modern airplane configuration and first lift-drag vector diagram in history

"Chauffeurs"

19th century flying machine inventors who were obsessed with "brute force"-given enough thrust (or horsepower) from an engine, the airplane could be forced into the air.

circular argument:

more power → more weight → must move faster to generate lift → (back to more power)

idea was to simply "chauffeur" the machine into the air, with no thought to controllability once it was in the air.

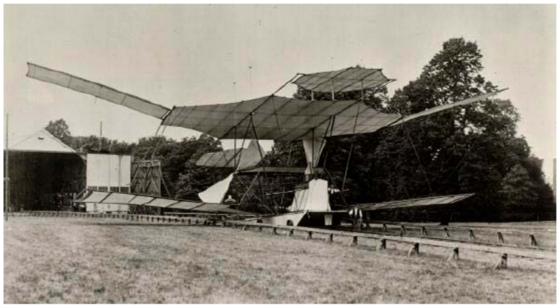
The failure of this philosophy led to the idea of developing engines with more power but less weight.

T/W ratio is now a critical parameter in aircraft design.

Hiram Maxim

Epitomizes the chauffeur philosophy of the late 1800s.

Maxim invented the first fully functional machine gun. He used the fortune generated by this invention to fund the design of flying machines.



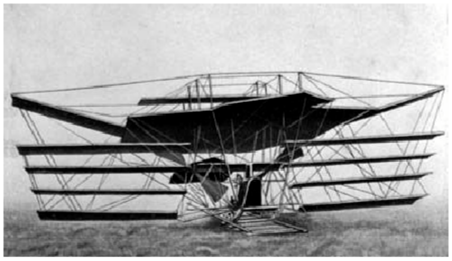
2 180 hp engines

2 propellers

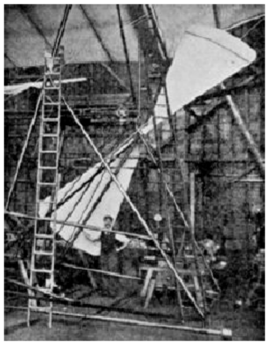
TOGW = 8,000lbs

T/W = ??

Hiram Maxim



Maxim's machine with all lifting surfaces



One of the propellers

"Airman's Approach"

Philosophy that, in order to design a successful flying machine, it is necessary to fly unencumbered by a power plant-learn to fly before you put an engine on the aircraft.

Antithesis of the chauffeur philosophy

Otto Lilienthal, a German mechanical engineer, designed and flew the first successful gliders in history.

- clearly demonstrated the aerodynamic superiority of cambered (curved) airfoils in comparison to flat, straight surfaces
- Lilienthal's book *Bird Flight as the Basis of Aviation* was far and away the most important and definitive contribution to the budding science of aerodynamics in the 19th century.
- Published first drag polars ever.

Lilienthal

Advanced the science of aeronautics and flight by leaps and bounds. His university degree lent credibility to his studies, and his public demonstrations helped ease people into the idea of manned flight.

He died in 1896, after stalling a glider he was flying. At the time, he was working on a powerplant for one of his gliders, but further research revealed it was an ornithopter-like flapping concept.

Samuel P. Langley

Was contracted to build a flying machine for the U.S. government.

Began a series of aerodynamic experiments in 1887, using a whirling arm and published a book *Experiments in Aerodynamics* in 1890.

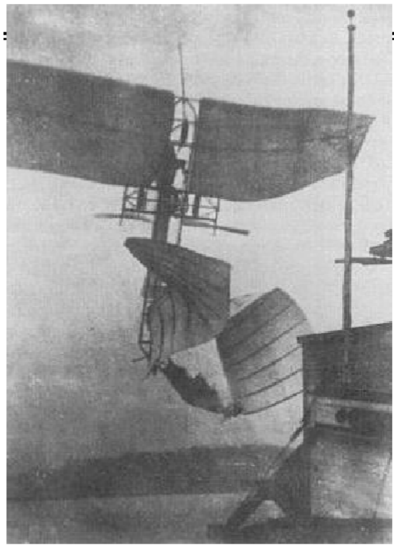
Was third Secretary of the Smithsonian Institution

Successful in flying several small scale, unmanned, powered aircraft, which he called *aerodromes*. These were the first steam-powered, heavier-than-air machines to successfully fly.

Along with Charles Manly designed and developed the best airplane powerplant until the beginning of World War I (124lb, 52.4 hp). T/W=???

Langley's attempt to build a manned aerodrome failed but had a superb powerplant, marginally good aerodynamics, but was structurally unsound.
Launched and crashed on Oct 7 and December 8, 1903

Langley Aerodrome



Langley deserves a lot of credit for his aeronautical work in the pre-Wright era.

Legacy of Langley is in the name of the NASA Langley Research Center and the Langley Theater at the Nat'l Air and Space Museum.

Langley's aerodrome shortly after launch

Era of Strut and Wire Biplanes

The Wright Brothers

The 1903 Wright Flyer ushered in the era of successful strut-and-wire biplanes- an era that covers the general period of 1903 to 1930.

Unlike Langley's full-scale aerodrome, there were no fatal "weak links" in the design of the Wright Flyer-they were the first true aeronautical engineers.

In the 1903 Wright Flyer they had gotten it all right-the propulsion, aerodynamic, structural, and control aspects were carefully calculated and accounted for during its design

Propulsion was achieved by a four-cylinder in-line engine designed and built by Orville Wright. It produced close to 12 hp and weighed 140 lbs. T/W = ??

The engine drove two propellers via a bicycle-like chain loop.

The Wright Brothers

The propellers were masterpieces of aerodynamic design. Wilbur Wright was the first person to recognize the fundamental principle that a propeller is nothing more than a twisted wing. He conceived the first viable propeller theory and blade element theory.

Prop efficiency of 70%
Langley's prop efficiencies were on the order of 52%
What are modern prop efficiencies?

The control features of the Wright Flyer are also one of the basic reasons for its success. They were the first to recognize the importance of flight control around all three axes of the airplane: pitch control, yaw control, roll control. They were the first to appreciate the value of roll control and used wing warping.

The structural features were patterned partly after the work of Chanute and their own experience designing bicycles-another example of evolutionary design.

Wright Brothers-Aerodynamics

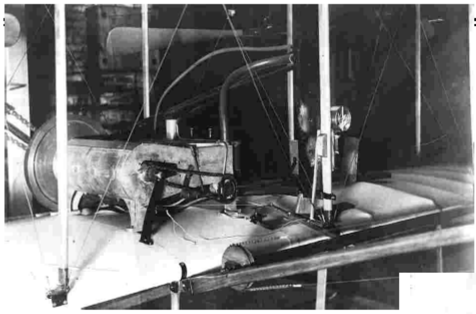
The Wrights were well aware that the major measure of aerodynamic efficiency is the lift to drag ratio, L/D, and did three things:

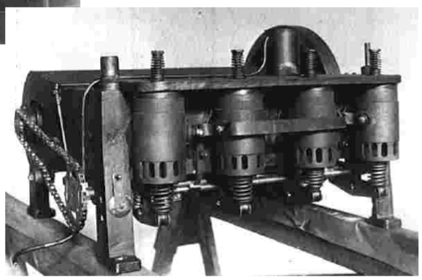
Chose an airfoil shape that, based on the collective data from their wind tunnel tests, would give a high L/D (on the order of 6)

Chose an aspect ratio of 6 for the wings, although they didn't know that by increasing the aspect ratio from 3 to 6, they reduced the induced drag by a factor of 2 (Prandtl showed this in Germany 15 years later).

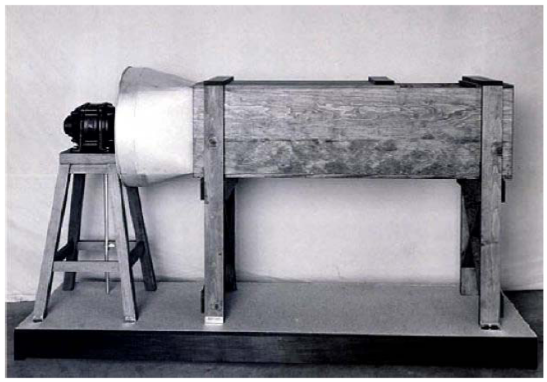
Very conscious of the importance of parasite drag, which in their day was called head resistance (used empirical formulas obtained from Octave Chanute in his book Progress in Flying Machines). To combat drag, they decided to fly prone (laying down). They did not, however, realize the high drag caused by the wires.

Wright Flyer Engine



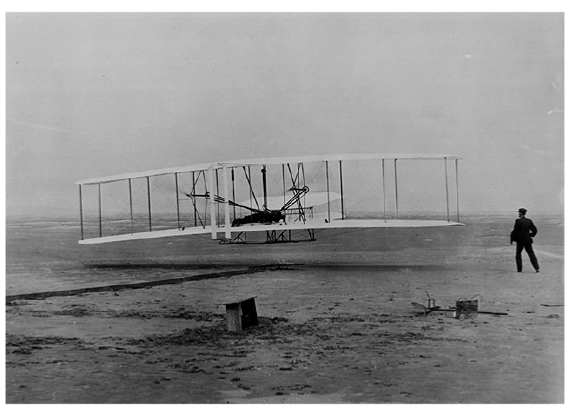


Wright Brothers Wind Tunnel



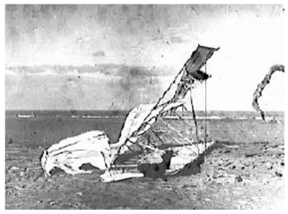
Replica of Wright Brothers Wind Tunnel

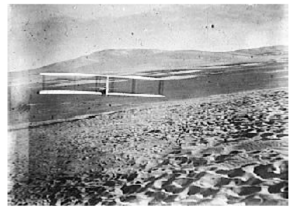
The Wright Flyer

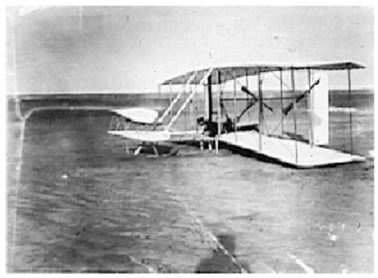


Famous First Flight photograph, 1903

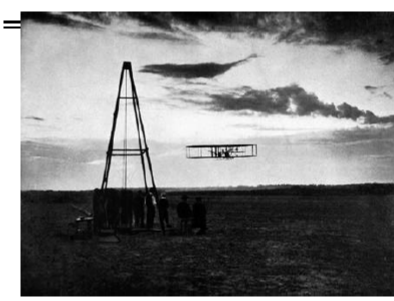
The Wright Flyer







The Wright Flyer



Other Developments Following Wright Bros.

Wing warping method of control quickly supplanted by ailerons in most other aircraft (Glenn Curtiss on hi June Bug airplane, etc)

Open framework of the fuselage was in later designs enclosed by fabric, as an attempt at "streamlining" the airplane, although this was based on intuition.

The demands for improved airplane performance during World War I gave a rebirth to the idea of "brute force" in airplane design. The focus was on more powerful engines.

Strut and wire biplanes were the mainstay of aeronautics for the decade following World War I, largely due to the conservative nature of many early aircraft designers.

Other Developments Following Wright Bros.

The famous French airplane designer, Louis Brequet, however, appreciated the need to bring to a minimum the value of D/L and even called for retractable landing gear in 1924.

Sponsorship of air races, such as the Schneider Cup races, resulted in specfically designed racing airplanes and they substantially contributed to the demise of the era of strut and wire biplanes and the beginning of mature, propeller driven aircraft.

Era of the Mature Propeller Driven Airplane

This era ecompasses the time between 1930 and 1950

During this time, airplane design matured, new technical features were incorporated, and the speed, altitude, efficiency, and safety of aircraft increased markedly

The 1930s are considered by many aviation historians as the "golden age of aviation"

The maturity of propeller-driven airplanes is due to NINE major technical advancements, all of which came into fruition during the 1930s.

9 Major Technical Advancements

FIRST- Cantilevered-Wing Monoplane:

Bleriot first crossing of the English Channel (1909) in a monoplane caused a surge of popularity; however, an inordinate number of crashes precipitated by structural failure of the monoplane wings (1913) helped to reinforce distrust.

Hugo Junkers designed and built the first all steel cantilever monoplane (1915).

Ford Trimotor first widely accepted monoplane in U.S. (1926). Rockne killed.

Boeing Monomail (1930) embodied two technical developments:
- all metal stressed skin construction
- retractable landing gear

9 Major Technical Advancements

SECOND- Retractable Landing Gear

THIRD- Cowling for Radial Piston Engines:

Clark designed a primitive cowling in 1922 for the Dayton-Wright XPS-1

In 1927 Townsend designed a ring that was installed on the Boeing Monomail (noticable decrease in drag with no interference with engine cooling)

Major breakthrough in engine cowlings was due to NACA in U.S. through a systematic series of wind tunnel tests with the objective of understanding the aerodynamics of engine cowlings and designing an effective shape for them.

NACA results indicated 60% reduction with full cowling and by proper design of the cowling enhanced cooling of the engine could be obtained

9 Major Technical Advancements

FOURTH- Variable Pitch Propeller

For fixed propeller the twist is designed so that each airfoil section is at its optimum angle of attack to the relative airflow, usually approximately to maximum L/D of the airfoil.

However, a fixed pitch propeller is operating at maximum efficiency at only its design speed; a tremendous disadvantage of a fixed pitch propeller.

To vary the pitch of the propeller during flight to operate at near-optimum conditions is not an easy mechanical task. The first practical and reliable mechanical device for varying propeller pitch was designed in 1933. Boeing 247 transport used variable pitch propeller to improve its mountain flying efficiency.

Constant speed propellers debuted in the 1930s

9 Major Technical Advancements

FIFTH- High Octane Aviation Fuel

Engine pinging caused permature ingition as early as 1911

Tetraethyl lead found to reduce engine knicking- GM and Standard Oil formed new company, Ethyl Gasoline Corporation, to produce “ethyl” gas with lead

Army Air Corps (1930) adopted 87 octane gas as its standard fuel; in 1935 raised to 100 octane. 100 octane allowed much higher compression ratios inside the cylinder head, and hence more power for engine.

Introduction of 100 octane fuel, as well as other technological improvements, allowed Curtiss-Wright to increase power of its R-1820 Cyclone engine from 500 to 1,200 hp in the 1930s.

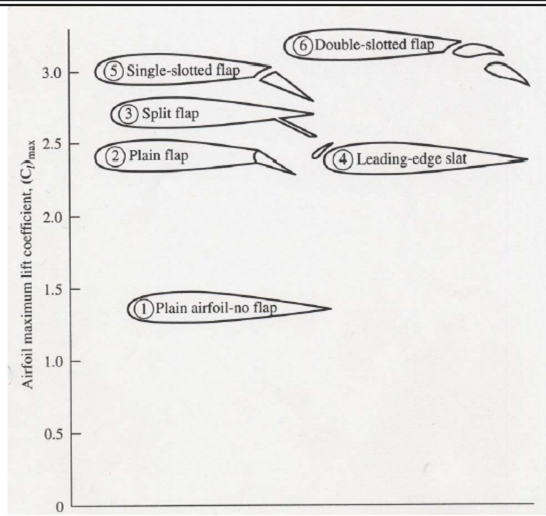
9 Major Technical Advancements

SIXTH- Development of High Lift Devices

Wing area must be large enough to provide sufficient lift at takeoff and landing. This criterion dictates the ratio of airplane weight to wing area (wing loading, W/S).

Cruise speed requires less wing area as higher speed causes larger pressure differences resulting in excess wing area. Therefore, high lift devices relieve this problem by allowing wing area sized for cruise.

Types of Flaps



9 Major Technical Advancements

Basic Plain Flap: evolved directly from the trailing edge ailerons. Standard in Fairey airplanes from 1916 onward.

Single-slotted flap: developed around 1920 independently by three different people: Lachmann (German pilot 1917-patent first rejected), Handley Page (England, claimed 60% increased lift), and O. Mader (Junkers engineer 1919-21).

Split Flap: invented in U.S. by Orville Wright in 1920. Increased both lift and drag. Used on Northrop Gamma, Lockheed Orion, DC-1 and DC-3, others in 1930s.

Fowler Flap: Harlan D. Fowler, Army Air Corps engineer
increased effective camber of wing
increased wing area

Only major advancement since 1930s was combination of Fowler flap with slotted flap, and use of more than one slot. Boeing 727 triple slotted Fowler flap

9 Major Technical Advancements

SEVENTH- Pressurized Airplane

Cruising altitude limitd to 18,000 feet or less without pressurization. First pilot to use pressurized suit: Wiley Post. Lockheed 10E Electra modified was first pressurized cabin and had service ceiling of 35,000 feet.

EIGHTH- Supercharger

Mechanical pump that simply compressed the incoming air before it went into the engine manifold, thus allowing pressurization of the engine. High priority in the 1930s and 1940s. Major NASA development program. All high performance military aircraft in WWII were equipped with superchargers as a matter of necessity.

9 Major Technical Advancements

NINTH- Laminar Flow Airfoils

Two types of flow: laminar flow and turbulent flow in the boundary layer (Prandtl 1904). About 99% of the boundary layer along wings and fuselage in flight is turbulent, creating high skin friction drag. NACA developed laminar flow airfoils which reduced airfoil drag by almost 50%. However, in practice laminar flow wing never payed off in drag reduction (manufacturing imperfections, bugs, etc).

Laminar flow airfoils turned out to be very good on high speed airfoils. They had a much higher critical Mach number and delayed onset of compressibility problems encountered by many high-speed airplanes in the early 1940s.

Era of the Jet Propelled Aircraft

Many of the famous WWII aircraft were designed well before the war, and had no inherently new matures compared to the modern propeller driven aircraft. New designs were frozen at the advent of the war to allow for mass production of existing designs.

For the U.S. WWII can be characterized as a period of intensive design improvements and refinements rather than a period of innovation.

However, the Germans and the British had a different perspective, out of which was born the era of the jet propelled aircraft.

Some Aircraft of the Era

Messerschmitt ME 262A

Republic P-47D Thunderbolt

Some Aircraft of the Era

North American P-51 Mustang

North American F-86 Sabre

The Jet Engine

The invention of the jet engine caused a revolution in airplane design and performance. It was the most substantial impact on aeronautics since the Wright Brothers.

Conventional propeller driven airplanes had a major speed limitation: when the speed of the propeller tips approached or exceeded the speed of sound, shock waves would form at the tips, and propeller efficiency would plummet. Jet propulsion opened the way toward efficient transonic and supersonic flight.

The jet engine was developed independently by two people:

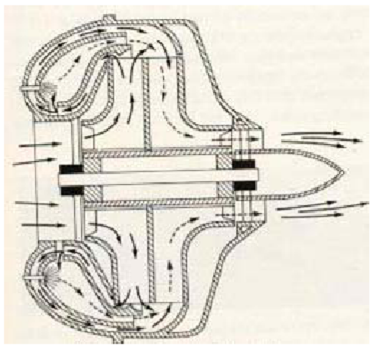
Frank Whittle (England, 1930 patent)

Hans von Ohain (Germany) with Heinkel had first flight test in 1939

The Jet Engine

British Bolster E.28/39 flew with Whittle engine in 1941. These two first flights in Germany and Britain began the jet age, although it was 1944 before a jet aircraft was deployed in any numbers with the German Messerschmitt 262

- max speed of 540 mph
- 1400 aircraft produced



Frank Whittle's patent drawing

Increasing the Speed

The era of jet propelled aircraft is characterized by a number of design features unique to airplanes intended to fly at, near, or beyond the speed of sound.

Swept Wing

- subsonic - fly closer to the speed of sound, increased the airplane's critical Mach number
- supersonic - can keep wing's leading edge inside the Mach cone from the nose of the fuselage
- for high subsonic or supersonic, and airplane with a swept wing can fly faster than one with a straight wing, everything else being equal
- first introduced in a public forum in 1935 by Adolf Bussman, German aerodynamicist. Later classified by German Luftwaffe as a military secret
- R.T. Jones, NACA aerodynamicist, worked out swept wing theory toward end of WWII
- North American Aircraft F-86 world's first successful operational swept wing aircraft in 1948.

Increasing the Speed

Sound barrier broken in 1947 by Capt. Charles (Chuck) Yeager in Bell X-1 rocket powered airplane.

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC72-3431 Date: 1947 Photo by: USAF photo by Lt. Robert A. Hoover

X-1 in flight

Increasing the Speed

Eight years later the Lockheed F-104 was first fighter airplane capable of sustained flight at Mach 2.

F-104 exhibited best qualities of good supersonic aerodynamics:

a sharp, pointed nose
4% thick airfoil
slender fuselage
extremely thing and sharp wings
straight wing, but very low aspect ratio

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC90-224 Date: 1990

F-104

Increasing the Speed

Delta wing concept also came out of Germany during 1930s and 1940s.

In 1930, Dr. Alexander Lippisch designed a glider delta wing

20 degrees sweep

Along with German swept wing data, the delta wing technology was transferred to the U.S. after WWII, “gifts to the victors”.

First practical delta wing was Convair F-102

Increasing the Speed

Although the Convair F-102 employed the delta wing, it could not fly supersonic without utilizing the “area rule” concept (R. Whitcomb).

The area rule was one of the most important technical developments during the age of jet-propelled airplanes.

Whitcomb and area ruled model

fishing lures designed using area rule principles

The Emergence of Boeing

One of the most tragic stories in the annals of airplane design occurred when three de Havilland Comets failed structurally in 1954. The problem was found to be structural failure of the fuselage when pressurized.

Failures set back de Havilland and allowed Boeing to emerge as the world's leading supplier of commercial jet aircraft.

Boeing's bold and risky decision to privately finance and build a commercial jet prototype, designated model 367-80 or Dash 80, was based on building a swept wing jet bomber for the Air Force (B-47, B-52)

Boeing 707 was the production aircraft designation. They brought in Pan American Airlines as a risk sharing partner, who brought the aircraft into service.

The 707, with its swept wings and podded engines mounted on pylons beneath the wings, set the standard design pattern for all future large commercial jets to present day.

Boeing 707

Boeing 747

Boeing's second bold move was to "go for the big one" in 1966 after losing to Lockheed in the Air Force C-5 competition. Boeing 747 first flew in 1969 and entered service with Pan Am in 1970.

Supersonic Transports (SSTs)

In the 1960s, the U.S., England, and France began development of SSTs.

The Tupolev Design Bureau rushed an SST design into production and service. The Tu-144 first flew on Dec 31, 1968. More than a dozen of these aircraft were built, but none entered extended service, presumably due to unspecified problems. One Tu-144 was destroyed in a dramatic accident at the 1973 Paris Air Show.

The U.S. government orchestrated a design competition for an SST. The Boeing 2707 was the winner in 1966. Design turned into a nightmare for Boeing. First a variable sweep wing was pursued and then junked, then the new design was caught in an upward spiral of increased weight and development cost. When predictoins of final development cost hit about $5billion, Congress terminated the program.

Tu-144

The Concorde

The first, and so far only, SST to see long term service is the Anglo-French Concorde.

- Designed to cruise at Mach 2.2
- Carries 125 passengers
- First flew and exceeded Mach 1 in 1969
- Exceeded Mach 2 in 1970
- In service since 1976
- Original orders for 74 aircraft were reduced when world energy crisis skyrocketed cost of aviation fuel

Concorde can be considered a technical but not financial success.

Represents an almost revolutionary (but not evolutionary) design

The Concorde designers had at least 15 years of military airplane design experience with such features to draw upon.

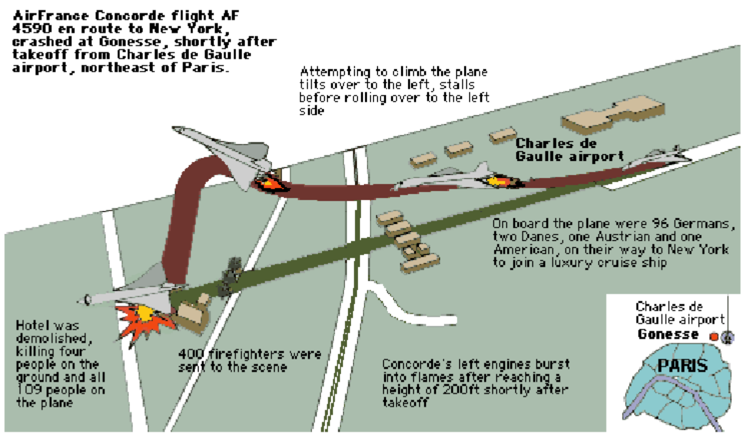
The Concorde

Incorporated good supersonic aerodynamics: sharp nosed slender fuselage and cranked delta wing with a thin airfoil

The Concorde Crash

On July 25, 2000, the first ever crash of the Concorde occurred.

The Concorde Crash



The Future of SSTs

The design of the next generation SST is considered one of the greatest challenges in aeronautics.

The High Speed Civil Transport (HSCT) being studied by NASA and industry (and GT!) since 1989 was once again put on hold in 1999.

So…why is this design so difficult?

Unconventional Concepts/Innovative Designs

VTOL-Vertical TakeOff and Landing. These are fixed wing aircraft and helicopters are NOT considered VTOL in this book.

A good example of this genre is the British Harrier, in continuous service since the 1970s.

Utilized by the Royal Air Force and Royal Navy

The AV-8 was adapted and manufactured by McDonnell-Douglas in the early 1980s and is in service with the U.S. Marine Corps.

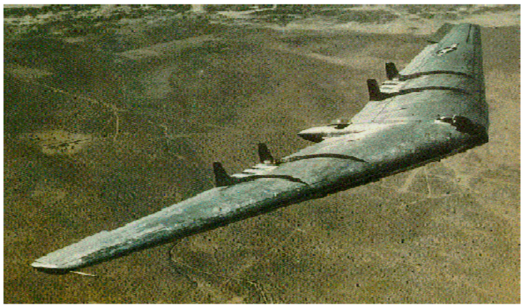
Jet exhaust from the single Rolls Royce Pegasus jet engine passes through four nozzles, two located on each side of the engine. Vanes in the nozzles deflect the exhaust both downward for vertical flight and horizontally for conventional flight.

Harrier

Flying Wing

Concept: fuselage is primarily a drag-producing device. If the whole aircraft were one giant wing, maximum aerodynamic efficiency could be achieved.

Jack Northrop was famous for his flying wing concepts designed in the early 1930s. During and after WWII, Northrop built several flying wing bombers.



YB-49

Flying Wing

Longitudinal stability and control normally provided by the horizontal tail and elevator at the end of a conventional configuration must instead be provided by flaps and unusual curvature of the camber line near the trailing edge of the flying wing.

These issues caused enough stability and control problems that flying wings were not viable until those produced recently. Modern technology allows the design and control of unstable aircraft-fly by wire.

Modern Flying Wing-B2 Bomber

Stealth Aircraft

Primary objective of stealth aircraft is to have the lowest possible radar cross section possible.

Designs typically feature sharp edges and flat angled surfaces. These are designed to reflect radar waves away from the source rather than back to it.

Designs also feature radar absorbing materials and paint.

Realize that good subsonic aerodynamic design is embodied by rounded leading edges, smoothly curving surfaces, and slender, streamlined shapes. Note that the shapes of stealth aircraft do not conform to these ideas. This is an example of the tradeoffs that must occur in any aircraft design. To achieve a lower RCS, aerodynamic performance is sacrificed in stealth aircraft.

Sometimes these airplanes are referred to as "airplanes designed by electrical engineers".

Stealth Aircraft

Ultralights

Ultralights came into being in the 1970s on the heels of the sport of hangliding, when pilots started adding small engines on foot launched hang gliders. The vehicles developed, became faster, more maneuverable, and landing gear were added. In 1982 the FAA formally recognized ultralights as a flight category and implemented regulations.

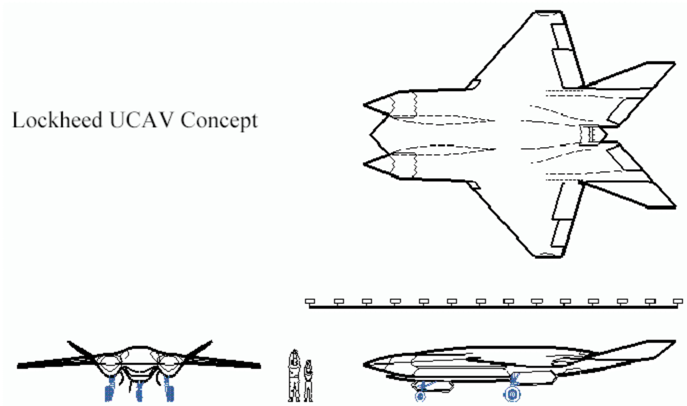
Ultralights

UAVs

Uninhabited Air (or Aerial) Vehicles are called UAVs. There is a lot of attention being paid currently to the design of these vehicles, primarily for military applications.

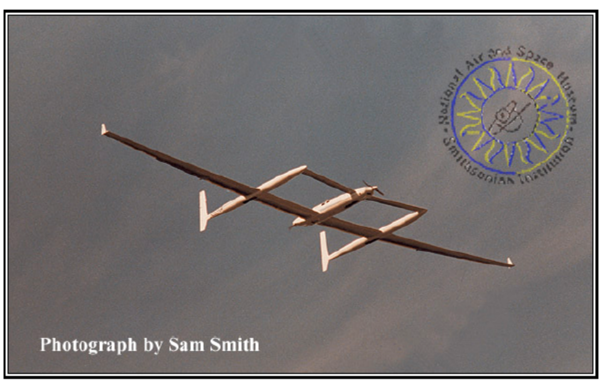
Predator

UAVs



Point Designs

These are aircraft that are designed for one specific capability, limiting their usefulness outside that particular capability.



Rutan's Voyager

Future Challenges

Hypersonic Flight

NASA X-30 concept

Micro Air Vehicles

Future Challenges

Biomimetic or
Morphing Vehicles