University of Liege Department of Aerospace & Mechanical Engineering

Aircraft Design Introduction to Conceptual Design & Aviation History

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Aircraft Design - Introduction & History

- Why lectures on aircraft design?
 - Aircraft design requires the accounting of multi-field interactions
 - Aerodynamics
 - Propulsion
 - Structure
 - Costs management
 -
 - All these different fields have to be fully integrated during design



- The best plane is fast, fuel efficient, reliable, inexpensive to build, inexpensive to operate, comfortable, noiseless,, but it does not exist!





Goals of the classes

- What do we want to design?
 - Examples:
 - 1907, the Army ordered to the Wright's brothers:
 « one (1) heavier than air flying machine to be delivered in 6 1/2 months ».
 - 1932, TWA orders the DC-1 with a 1-page list of requirements
 - Nowadays, requirements are reported in complex manuals with
 - Customer needs
 - Certifications
 - Performances
 - Maintenance
 - Sub-systems properties,

TRANSCUNTINENTAL & WEST RH AIR, INC.

General Performance Specifications Transport Plane

- <u>Type</u>: All metal trimotored monoplane preferred but combination structure or biplane would be considered. Main internal structure must be metal.
- Power: Three engines of 500 to 550 h.p. (Mespe with 10-1 supercharger; 6-1 compression 0.K.).
- Meight: Gross (mzimm) 14,200 lbs.
- Weight allowance for radio and wing mail bins 350 lbs.
- 5. Weight allowance must also be made for complete instruments, night flying equipment, fuel expectity for druising range of 1060 miles at 150 m.p.h., erew of two, at least 12 passengers with confortable seats and ample room, and the usual miscollaneous equipment carried on a passenger plane of this type. Payload should be at least 2,300 lbs. with full equipment and fuel for maximum range.
- 6. Performance

Top speed see level (minimum)	185 a.p.h.
Cruising speed sea level - 79 % top speed	146 m.p.h. plus
Landing speed not more than	65 m.p.h.
Rate of climb sea level (minimum)	1200 ft. p.m.
Service ceiling (minimum)	21000 ft.
Service celling may two engines	10000 rt.

This plane, fully loaded, must make satisfactory take-offs under good control at any TWA airport on any combination of two augines.

Kansas City, Missouri. August 2nd, 1932



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• How do we want to design?

- Requirements depend on the aircraft finality

	Civil	Military
Dominant design criteria	Economics and safety	Mission accomplishment and survivability
Performance	Maximum economic cruise	Adequate range and response
	Minimum on-design penalty	Overall mission accomplishment
Airfield environment	Moderate-to-long runways	Short-to-moderate runways
	Paved runway	All kinds of runway surfaces
	High-level ATC and landing aides	Often Spartan ATC, etc.
	Adequate space for ground maneuver and parking	Limited space available
System complexity & mechanical design	Low maintenance-economic issue	Low maintenance- availability issue
	Low system cost	Acceptable system cost
	Safety and reliability	Reliability and survivability
	Long service life	Damage tolerance
Government regulations	Must be certifiable (FAA, etc.)	Military standards
and community acceptance	Safety oriented	 Performance and safety
	Low noise mandatory	 Reliability oriented
		Low noise desirable
		 Good neighbor in peace
The Se		•Detectability in war



Goals of the classes

- Design stages
 - Conceptual design
 - Purposes
 - Define the general configuration (tail or canard, high or low wing, ...)
 - Analyze the existing technologies
 - Estimate performances for the different flight stages
 - Accurate estimation of the total weight, fuel weight, engine thrust, lifting surfaces, ...
 - How
 - Limited number of variables (tens): span, airfoil profile, ...
 - Accurate simple formula & abacuses
 - Preliminary study
 - Higher number of variables (hundreds)
 - Starting point: conceptual design
 - Numerical simulations
 - Detailed study
 - Each component is studied in details





- Multidisciplinary optimization
 - Different possible measures of the performance
 - Minimum weight (empty or at take off)
 - Minimum operating cost (direct or total)
 - Maximum profits or maximum ROI
 - Maximum payload per €
 - How to maximize the performance?
 - Trial-&-error?
 - Experiment
 - Research
 - Numerical optimization
 - Has to account for an airplane complexity
 - Has to account for a maximum of criteria
 - Example, the weight was minimized without accounting for stability
 - Optimum or local optimum?
 - Does not innovate
 - Most of the time the requirements constrain the design
 - Is (only now) starting to become a standard tool for engineering design
 - Current aircraft design results from centuries of researches
 - (Almost) all aircrafts look the same







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From birds to planes

- The ornithopter
 - Wings produce
 - Lift &
 - Thrust by flapping
 - ~1500, Leonardo da Vinci
 - Human is not strong enough to attach wings at the arms, so mechanical devices are needed
 - Numerous failures

- 1513, da Vinci studied the possibility of using a fixed wing
 - Guess the lift and drag
 - Wing flapping should not contribute to lift
 - Drag is proportional to the surface







- Aerodynes (heavier than air): First gliders
 - 16th century, da Vinci, drag proportional to surface
 - 17th century, researches on drag
 - Galileo Galilei: Proportional to density & depends on velocity
 - Huygens, Hollande & Mariotte, France: Proportional to the velocity square
 - ~1804, Cayley, UK pioneered aeronautics
 - Whirling arm to measure aerodynamic forces
 - Identified thrust, lift & drag
 - Measured attack angle effect
 - First cambered airfoils



- Dihedral wings for roll stability
- Studied the effect of the CG location on pitch stability
- 1853, built a glider
 - 1979, replica actually flew







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Aeronautics pioneers

- Aerodynes (heavier than air): First gliders (2)
 - 1866, Otto Lilienthal, Germany
 - Cambered-airfoil polar diagrams
 - Not accurate
 - Built gliders (2000 flights)
 - 1896, passed out during a flight













Aeronautics pioneers

- Aerodynes (heavier than air): First concepts
 - ~1871, Alphonse Pénaud, France
 - Build toys
 - Roll stability: dihedral wing
 - Pitch stability: horizontal tail with negative angle of attack
 - Propulsion
 - 2-blade propeller
 - Powered by twisted rubber strands



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Aerodyne configuration: Cayley & Pénaud vs 21st century design

The centre of gravity was varied by sticking a weight with a sharp point into the stick whole weight was 3.82 oz., and when the centre of gravity, G, was under such part c kite as left 75 [square] inches on the anterior part and 79 [square inches] behind it, and the tail at an angle of 11.5°..., then if a velocity of 15 feet per second was given to it horizontal direction, it would skim for 20 to 30 yards supporting its own weight, a pointed downward in an angle of 18°, it would proceed uniformly in a right line for with a velocity of 15 feet per second.⁷



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Aeronautics pioneers

• Aerodynes: First propulsions attempts

- 1874, France, Felix du Temple de la Croix
 - Build the monoplane
 - Steam-powered
 - First self powered take off
 - Short distance "flights"
- 1896, USA, Langley
 - Used the whirling arm to design the plane
 - Engine power should be equal to drag times velocity
 - Built an aerodyne
 - Unmanned
 - Steam-powered
 - Catapulted at take off
 - 1000-m long flight over the Potomac
 - Numerous possible adjustments
 - CG location
 - Angles of attack
- 1897, France, Ader,
 - Built l'Éole III
 - 100-m long uncontrolled "flight"
 - 2x 20-hp-steam engine











First flights

- First success: the Wright brothers, USA
 - Success due to 2 main factors:
 - Engineering approach
 - Use of wind tunnels,
 - Attempts on gliders
 - Piston engine was available
 - Powerful and light
 - 1903 flight (Flyer I)
 - Canard and negative dihedral
 - Roll control by twisting the 2 wings:
 « wing warping »
 - Wing warping and rudder coupled
 - 37-m long flight
 - Unstable to pitch
 - Take off only with front wind
 - 12-hp engine









First controlled flights

- Louis Blériot, France
 - 1908, contest between
 Blériot, Wright &
 Santos Dumont
 - Flights
 - Of 20 km
 - At 80 km/h
 - 1909, Blériot XI
 - Crossed the Channel
 - Military aircraft
 - Observation
 - Elevators & wing warping controlled by the yoke
 - Rudder controlled by pedals
 - Blériot pioneered the control commands
 - Yoke controls
 - Elevators (pitch)
 - Ailerons (roll)
 - Pedals control
 - Rudder (yaw)









• WWI

- Airplanes became specialized
 - Reconnaissance
 - Fighters
 - 1917, Fokker DRI
 - » 180 km/h at 6000 m
 - Bombers
 - 1917, Gotha G.V
 - » 140 km/h at 6500 m
 - » Machineguns
 - 1916, Handley Page O/400
 - » 150 km/h at 2500 m
 - » 900 kg of bombs









- The first airlines and airmail services
 - 1911, India, Pecquet
 - Carried 6500 mails (13 km)
 - 1916, USA, Boeing
 - Founded the Pacific Aero Products Co
 - Wood seaplane (biplane)
 - Seaplanes can easily find long runaways
 - 1917, the company became the Boeing Airplane Company
 - 1927, it became the United Aircraft and Transport Corporation
 - 1918, airmails carried by the US postal
 - 4 pilots
 - DC/New-York
 - De Havilland DH4
 - 1918, France, first flights of the "aéropostale"
 - Toulouse Barcelona, and then to Casablanca & Dakar
 - To south America, transport by
 - Boat between Dakar and the Brazil
 - Airplanes between Brazil and Chile







- The first airlines and airmail services (3)
 - 1919, foundation of KLM
 - 1920, London-Amsterdam
 - Airco DH 16, 4 passengers
 - Warm clothes and earplugs
 - 1919, Atlantic crossing
 - With multiple stops
 - WWI: boats were threatened by U-boats
 - 1 NC out of 3 (the NC-4) succeeded
 - 15-day long trip
 - 1927, New-York Paris
 - First atlantic crossing without stop
 - 33-hour long trip
 - Lindbergh, pilot of the US Postal
 - On the Spirit of St Louis



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- National Advisory Committee for Aeronautics – 1915, foundation of N.A.C.A.
 - USA wanted to catch up with Europe
 - 1915 1950, airfoils tested in wind tunnels
 - 1933, 4-digit NACA airfoils
 - 1st digit: maximum camber as percentage of the chord
 - 2nd digit: distance of maximum camber from leading edge in 10% of chord
 - 3rd & 4th digits: maximum thickness as percentage of the chord
 - 1935, 5-digit NACA airfoils
 - High lift airfoils
 - 2nd & 2nd bis: distance in 5% of chord
 - 1939, 6-digit laminar airfoils
 - Maximum thickness further back
 - Lower drag
 - Efficient at high subsonic velocity
 - First flight on Mustang P51 (1942)
 - … (see next slides)
 - 1958, became the N.A.S.A.







The first airliners

- 1933, Boeing 247
 - Semimonocoque structure in anodized aluminum
 - 1931, wood laminate is forbidden after the TWA599 accident
 - Moisture had leaked into the interior of one wing
 - Weakened the glue bonding the spars
 - Wing of the Fokker entered into flutter
 - Cantilevered wing with flaps, elevators with trim
 - Deicing & retractable landing gear
 - Autopilot (rudder & elevators)
 - Cruise at 300 km/h (3000-m altitude)



_ 1938, Boeing 307 with pressurized cabin (340 km/h at 8000 m)

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- The first airliners (2)
 - The B247 are sold only to United Airlines (former part of Boeing)
 - 60 aircraft at \$60000 each
 - TWA ordered the DC-1 at Douglas Corporation
 - 1934, production model is the DC-2
 - 2 x 710-hp engines
 - First comfortable airliner
 - Los-Angeles/New York in 18h







Air supremacy became strategic Spitfire



- Elliptic wing
 - Already used in Germany
 - Reduces the (lift) induced drag
 - » Over/under-pressure on in/extrados induce
 - vortex at wing tips» Create a downwash &
 - a drag
 - » This drag is higher at low velocity when the angle of attack is higher



Bf109 Messerschmitt



- Straight leading edges & small wing area
 - Reduce parasitic drag (friction & pressure)
 - » This drag is important at high velocity
 - » Wing efficient at highvelocity





- Air supremacy became strategic (2)
 Spitfire
- Elliptic wing stalls at once
 - Spitfire was subject to spin
 - » At high angle of attack one wing side stalls during yaw
 - A washout was introduced
 - » Wing roots at higher angle of attack than wing tips
 - » Wing roots stall first
 - » Ailerons remain efficient
 - » Pilot can reduce the yaw
- Thin airfoils
 - Root: 13% thick
 - Tip: 6% thick
- Monocoque (duralumin)

Bf109 Messerschmitt

- Short wing inefficient at low velocity
 - Use of high-lift devices

» Automatic slats



» Flaps



- Thin airfoils
 - Root 14.5% thick
- Monocoque (duralumin)





• Forces on control surfaces increase with velocity (1)

- WWI & WWII: mechanical control
 - Part of the control surface in front of the hinge
 - Horn balance (F4U corsair)
 - Hinge balance (Fokker Drl)
 - Drag increase
 - Optimized at low or high deflection (not both of them)
 - Servomechanisms
 - Flettner or servo-tabs
 - Move in the opposite direction of the control surface
 - B 29, Bf 109, B 707, ...
 - Introduction of a geared-spring so the felt force is constant per "g"







Forces on control surfaces increase with velocity (2)

- ~1945
 - All moving tail (XP 42)
 - Aerodynamic center close to the hinge
 - Felt control force
 - » Introduction of a bob-weight »: constant felt force per « g »
 - » Introduction of damping: felt force depends on the maneuver
 - Research in supersonic range
 - Servomechanisms inefficient as the flow is modified in supersonic
 - Development of hydromechanical devices
- Introduction of hydraulically assisted commands _
 - Hydraulic force acts on mechanical command (as in powered steering)
- 1945, P-80, for the ailerons; 1952, DH.106 Comet
 Introduction of hydromechanical command
- - The mechanical circuit commands a hydraulic one
 - 1947 F-86, 1966 SR-71; 1964 B727, 1972 A300, ...
 - Artificial feel devices
 - Avoid overstressing the structure
 - Springs, bob-weight, stick shaker, …





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• Forces on control surfaces increase with velocity (3)

- Fly-by-wire
 - Hydraulic circuit electrically actuated
 - 1950 Avro Vulcain
 - 1969 Concorde
 - Hydraulic circuit actuated by a computer (analogical or digital)
 - 1972, NASA modified F8
 - 1974, F16 with relax stability
 - Aircraft with negative stability in subsonic range
 - » Better maneuverability
 - 1984 A320, 1994 B777
 - Advantages
 - Lighter and safer (redundancy)
 - Can be adapted to flight regime
 - Relax stability possible
 - Allow suppressing
 - » Spinning and stall
 - » Pilot induced oscillations: pilot
 - corrections acting in opposite phase
 - with the aircraft response \implies series of increasing overcorrections in opposite directions







Compressibility effects

- 1887, Austria
 - Mach took a picture of a supersonic flow
- $\sim WWI$
 - Propeller tips experienced supersonic flow
- 1918, Caldwell & Fales, NACA,
 - High subsonic wind tunnel (700 km/h)
 - At critical Mach number
 - Increase of drag
 - Decrease of lift
 - Lift moves backward
 - Control surfaces inefficient at Mach > 1







Groundbreaking concepts during WWII: Propulsion

- Above 700 km/h propellers are inefficient
 - 1939, Henkel HE 178
 - First flight with radial turbojet
 - 1941-1944 Messerschmitt Me 262
 - Swept wing
 - Only to move the CG backward (engines on the wing)
 - Critical Mach: 0.86 (sweep was too low)
 - Automatic slats
 - Tricycle landing gear
 - When taking off the elevators were efficient only when the horizontal tail was horizontal
 - With old tailwheel configuration the pilot had to brake before taking off
 - Prevents ground looping







Groundbreaking concepts during WWII: Propulsion



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Altitude: 100 km

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Groundbreaking concepts during WWII: Propulsion

- Above 700 km/h propellers are inefficient (3)
 - Ramjet
 - Continuous thrust
 - Thrust only is V > 160 km/h
 - Concept, Lorin, 1911, France
 - 1941, Germany
 - Tested on a Dornier 17 at 200 m/s
 - Research on coal use
 - 1948, le Leduc 010, France
 - Launched in altitude
 - Mach 0.85



- 1964, SR71
 - The engine works as a ramjet for Mach > 3









Groundbreaking concepts during WWII: toward supersonic flights

The « sound barrier »

- End of the 30^s
 - Physics in transonic range is not known
 - Equations cannot be linearized
 - No computers
 - 1935, UK, Hilton explain to a journalist that drag increases in an unknown way close to Mach 1: this became the « sound barrier »
 - 1941, the P-38 accidents popularized the barrier hoax



- Bell X-1
 - Transonic research airplane
 - Rocket engine
 - Launched from a B29
 - All moving tail
 - Control in supersonic
 - 1947 Chuck Yeager reached Mach 1.06







Groundbreaking concepts during WWII: toward supersonic flights

- Compressibility effects
 - 1935, Volta conference
 - Busemann, Germany pioneered the concept of swept wing
 - Normal Mach number lower than aircraft Mach number
 - 1944, Me P1011
 - Wing with sweep angle of 30, 40 or 45° (to be changed on the ground)
 - 1944, Sabre F86
 - Original design failed due to the unswept wing
 - 1947, Prototype XP86
 - Swept wing (35°)
 - 1948, sound barrier broken during dive
 - Turbojet
 - GE J47, Thrust: 23 kN
 - Hydromechanical Controls





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Tailless aircrafts

- ~1930, Lippisch, Germany
 - No horizontal stabilizer
 - Glider (Storch, 1930)
 - Delta wing (Delta I, 1931)
 - Flying wing (Delta V, 1937)
 - Swept wing (Delta IV, 1932; Me 163, 1939)



- Act as
 - Elevator (if symmetric)
 - Ailerons (if antisymmetric)
- To act as elevators they have to be backward of the CG
 - → at wing tips
 - torsion
- When producing a positive (nose up) moment (take off), the lift is reduced









- Tailless aircraft: Δ wing
 - Advantages:
 - Mach > 1:
 - If enough swept: leading edges behind Mach cone generated by the aircraft nose
 low drag
 - Higher surface area compared to swept wing
 - Mach << 1:
 - At high angle of attack, a vortex is generated and remains stable on top of the wing flow at high velocity lift
 - Maneuverability at low velocity
 - Simple and robust structure





- Tailless aircraft: Δ wing (2)
 - Vortex generated at high angle of attack
 - Leading Edge eXtensions
 - SU 27, F18, ...
 - Chines of SR-71
 - Originally for stealth mode
 - Add maneuverability
 - Super maneuverability
 - At stall (high angles of attack) the plane can
 - Dive
 - Spin
 - Enter in deep stall (elevators are inefficient and the plane falls with a constant angle of attack)
 - Combination canard / LEX / fly-by-wire /
 - thrust vectoring
 - SU30, F22, ...
 - Some maneuvers are still possible during stall







- Pitch up or Sabre (F100) dance
 - Swept wing
 - Higher lift at wing tips
 - Flow from wing roots to wing tips
 stall first at tips
 - Wing tips are backward when stalling the lift moves ahead positive moment (nose up)

 Horizontal tail in turbulent flow inefficient (deep stall), particularly for T tail (F101)







 At high angle of attack the wing tips stall and the plane enters into pitch up mode





- Pitch up or Sabre dance (2)
 - Solutions: wing root has to stall first
 - Washout
 - Prevent boundary layer separation at tips
 - Slats at tips (higher camber
 - → lower attack angle)
 - Vortex generation on the extrados
 - » Vortilons (DC9, B717, Embraer) (act only at high angle of attack)
 - » Sawtooth (Super Etendard)
 - Prevent root to tip flow
 - Wing fences (SU22)
 - Forward swept
 - » 1984, X29
 - » Unstable in yaw (fly-by-wire)













• Swept wing: B47

- 1944, Army order
 - Design inspired from the B29
 - Drag too high ⇒ 35° swept
 - Turbojet
 - 6 x GE J47
 - Thrust: 23 kN each
 - Jato-assisted take off
 - Cruise: 900 km/h at 10000 m
 - Large body+swept Dutch-Roll
 - Roll & yaw are coupled
 - If too stable in roll (high wing), correction of the yaw (during stabilization) happens when rolls is already damped
 - Induces roll in the opposite direction
 - Solutions
 - » Yaw damping
 - » Negative dihedral
 - (less stable in roll)








Supersonic military aircrafts

- Variable-geometry aircraft
 - Supersonic bomber
 - Supersonic \implies swept or Δ wing
 - Taking off from an aircraft carrier
 unswept wing for higher lift
 (perpendicular flow higher & no transversal flow)
 - 1944, Me P1011
 - Wing with sweep angle of 30, 40 or 45° (to be changed on the ground)
 - Prototype captured and sent to Bell
 - 1951, Bell X-5, variable geometry aircraft
 - Subject to stalling
 - Aerodynamic center moves with sweep angle





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Supersonic military aircrafts

- Variable-geometry aircraft (2)
 - 1967, Supersonic bomber F111
 - Drawbacks
 - Displacement of the aerodynamic pressure center
 - Move the fuel
 - LEX
 - Glove vane (F14)
 - Mechanisms too complex
 - Heavy
 - Synchronizations issues
 - Solution
 - Oblique wing?
 - Symmetry problem







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- 1952, De Havilland 106 Comet 1, UK (1)
 - First jetliner, 36 passengers, pressurized cabin (0.58 atm)
 - Wrong aerodynamics at high angle of attack (takeoff)
 - 1953, 2 crashes: lift loss due to swept wing and air intakes inefficient



- Design issue
 - 1953, India, crash during storm
 - « Structural failure » of the stabilizer
 - The pilot does not "feel" the forces due to the fully powered controls (hydraulically assisted)
 - Fatigue due to overstress ?





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- 1952, De Havilland 106 Comet 1, UK (3)
 - 1954, August, ALYP roof retrieved from sea
 - Origin of failure at the communication window
 - Use of square riveted windows
 - Punched riveting instead of drill riveting
 - existence of initial defects

• 1958, Comet 3 et 4

- Round windows glued
- Fuselage thicker
- Too late



FIG. 12. PHOTOGRAPH OF WRECKAGE AROUND ADF AERIAL WINDOWS-G-ALYP.







- 1958, Boeing 707
 - First commercial success
 - 1952, prototype 367-80
 - Beginning of the 50s
 - Companies are comfortable with propellers, and are not pushing for turbojets
 - Boeing
 - Used turbojets successfully on the B47
 - Wanted to demonstrated viability of civil turbojets
 - 1958, B707 sold to Pan Am (\$ 4M)
 - 110 passengers
 - 4 JT3C turbojets
 - 52 kN each
 - Compression ratio 11.5
 - ~950 km/h (M 0.9) at 11000 m
 - 1960, introduction of turbofans
 - 1958, DC-8







- 1968, Boeing 737
 - 100-160 passengers
 - 6000 planes sold (2009)
 - Twinjet
 - Lower fuel consumption
 - 60-minute rule (at that time in the US)
 - 737-100: P&W JT8
 - 1985, 737-400, CFM56-3
 - High by-pass ratio (5:1)
 - Compression ratio 27.5





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- 1969, Boeing 747
 - 1963, Boeing sent a proposal for a troop transport aircraft
 - Able to be loaded from the nose
 - Lockheed won the contest (C-5 Galaxy)
 - Boeing recycled the project to build a wide-body civil airliner
 - ~400 passengers
 - New P&W JTD9 engines
 - High by-pass ratio
 - 207-kN thrust each (take off)
 - Cruise: 913km/h at 12000 m (Mach 0.855)







Transonic wave drag

- Flow is supersonic on the extrados
 - Shock wave ⇒ drag
- ~1960, Whitcomb, NASA,
 - Supercritical airfoils •
 - Flat extrados •
 - Camber at the trailing edge • (rear loading)
 - Reduce shock wave severity • (until raching divergence Mach)





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- Transonic wave drag (2)
 - Supercritical airfoils
 - 1973, tested on the F8



- Since the mid-70s
 - Used on civil airliners
 - A300, B767, B777, ERJ 145 ...





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• 1972, Airbus 300

- 1967, France, Germany & UK wanted to come back on the market
 - A300 project
 - 1968, the Ge CF6-5 engines are adopted instead of developing new high-by-pass RR engines with a thrust > 200kN
 - UK drew back temporarily
 - RR developed the engine and went bankrupt
 - Nationalization of RR
 - Hawker-Siddeley, UK, will produce the wing
 - 1970, Airbus was founded
 - France would produce the cockpit
 - Germany would produce the fuselage,
 - The Netherlands would produce the flaps & spoilers
 - Spain would produce the tail







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- 1972, Airbus 300 (2)
 - First wide-body twinjet (260 passengers)
 - Outside the USA, the maximum diversion distance followed a 90-minute rule (ICAO) and not a 60-minute rule
 - 1988, it became 120 or 180 minutes
 - The A300 became ETOPS-90 and then -180
 - Use of
 - Supercritical airfoils
 - Wingtip fences
 - Reduce wing tip vortex
 - → lower drag





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- Airbus (subsidies) VS Boeing (public)
 - In service
 - 1982, A320, Narrow body
 - First commercial success for Airbus
 - First fly-by-wire airliner
 - 1982, B767, Wide body twinjet
 - 1983, B757, Narrow body twinjet
 - 1992, A330/340, Two/Four-engine wide-body (common structures)
 - 1994, B777, largest wide-body twinjet (300-400 passengers), fly-by-wire
 - 1997, Boeing bought McDonnell Douglas
 old DC became B717, etc ...
 - 2007, A380
 - Two-deck configuration
 - 500-800 passengers
 - Four RR Trent 900
 - » 3-m diameter
 - » 300-kN thrust (take off)
 - 560 tons (MTOW)
 - 250/300-million €







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- Airbus (subsidies) VS Boeing (public) (2)
 - Most recent airliners
 - B787
 - 250-passenger twinjet
 - \$150 millions
 - 787 concept
 - » -20% fuel consumptionwas favored to the Sonic Cruiser
 - » 0.98 M
 - and to the 747X
 - » A380 competitor
 - 50% structural weight in composite
 - Cabin pressurized
 - » To 1800 m (usually 2600 m)
 - » With higher humidity level
 - Genx or RR Trent 1000 engines
 - » By-pass ratio 9.5:1,
 - A350, 250-passenger twinjet
 - 52% structural weight in composite







- ~1955, there had been a market for SST
 - At Mach 2, the consumption per km & per N thrust is the same than for a turbofan at Mach 0.85
 - 1962, 2 projects
 - La caravelle (Sud aviation)
 - Le 223 (Bristol)
 - They merged to reduce the costs —> Le Concorde
 - Development costed 6 times higher than the initial budget
 - Favored foundation of Airbus ?







- Supersonic business jets
 - For small aircraft sonic boom is less problematic
 - Demand from high-value passengers
 - Aerion/ Boeing / Spirit AeroSystems
 - Postponed (2025?) due to COVID



- Autonomous taxies for big cities
 - https://www.uber.com/be/en/elevate/







• Aircraft need in near future

Roland Berger estimations for 2030 BEFORE COVID

The baseline shows 21,760 aircraft to be delivered by 2030



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Near future

- Aircraft need in near future
 - Roland Berger estimations for 2030 POST COVID

Global air traffic is expected to be hit hard by the COVID-19 crisis



Source Roland Berger



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800 aircraft less

Near future

Aircraft need in near future

- Post-covid Airbus forecast (2023)
 - Demand for new passenger & freighter aircraft



 Asia, notably China and India will power growth, further shifting aviation's 'centre of gravity' toward Asia

https://www.airbus.com/en/products-services/commercial-aircraft/market/global-market-forecast



• Aircraft emission as of today

- The sector has already achieved huge efficiency gains (Airbus numbers)
 - 53% CO2 reduction per RPK Revenue Passenger Kilometre -since 1990
 - Only 25% of the current in-service fleet is the latest generation fuel efficient aircraft



https://www.airbus.com/en/products-services/commercial-aircraft/market/global-market-forecast

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• Airbus roadmap for zero-net emission





https://www.airbus.com/en/products-services/commercial-aircraft/market/global-market-forecast

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- Others
 - On-line
 - Applied Aerodynamics, Ilan Kroo, Stanford University, <u>http://www.desktopaero.com/appliedaero/preface/welcome.html</u>
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 - Quest for Performance: The Evolution of Modern Aircraft , Loftin Jr, SP-468, NASA Langley research center, <u>http://history.nasa.gov/SP-468/contents.htm</u>
 - Monographs in Aerospace History, Number 12, William Hewitt Phillips, <u>http://history.nasa.gov/monograph12/contents.htm</u>
 - Dryden Flight Research Center, http://www.nasa.gov/centers/dryden/home/index.html
 - http://www.century-of-flight.net/
 - <u>http://www.centennialofflight.gov/essay_cat/re_category.htm</u>
 - Books
 - Interactive Aerospace Engineering and Design, Dava Newman, McGraw-Hill Science, USA, ISBN 0-07-112254-0, 2002.
 - Synthesis of Subsonic Airplane Design, Egbert Torenbeek, Delft University Press, Kluwer Academic Publishers, The Netherlands, ISBN 90-246-2724-3, 1982.
 - A history of Aerodynamics, John Anderson Jr, Cambridge University Press, USA, ISBN 0-521-45435-2, 1997.





First attempts

- Hot air balloons (China, 2nd-3rd century, military signaling)
- Marco-Polo (13th century) kites are used in order to lift humans
- First wings
 - Icarus & Dedalus



Abbas Ibn Firnas (9th century, Spain)



- These two jumps failed (although the jumpers survive) due to the lack of stability (no tails)
 - 2008, Yves Rossy flew with rocketed wing











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From birds to planes

- The ornithopter
 - A few successes
 - Toys



- 2005, Yves Rousseau, France
 - First human-powered flight (seriously injured at second attempt)
- 2006, DeLaurier, Canada
 - First (jet-assisted) take off



- 1513, da Vinci studied the possibility of using a fixed wing
 - Guess the lift and drag
 - Wing flapping should not contribute to lift
 - Drag is proportional to the surface





Wind tunnels

- History of wind tunnels
 - 1746, UK, Robins
 - First whirling arms
 - Cayley, Langley, Lilienthal used this device
 - Low accuracy
 - 1872, UK, Wenham
 - First wind tunnel
 - Velocity 40 km/h, section 45x45 cm
 - Airfoil study
 - Lift applied at the front
 - Deduced erroneously that wings should be long and should have a reduced chord
 - Verified that such wings have a high lift to drag ratio
 - This ratio is higher than previous measures obtained with whirling arms
 - Proposed to use superposed wings (biplanes etc)
 - ~1880, UK, Maxim
 - Build a wind tunnel
 - Velocity 80 km/h, section 90x90 cm
 - Drag of a system > sum of the individual drags







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Wind tunnels

- History of wind tunnels (2)
 - ~1880, UK, Phillips
 - Used Wenham results
 - Built his own wind tunnel with convergent
 - Airfoil with extrados more cambered than intrados
 - 1893-1907, build multi-planes
 Failures
 - 1883, Reynolds, UK
 - Results obtained with scaled models in wind tunnels can be extrapolated to real dimensions if the flow is dynamically identical: Re = UL /v constant







• Canard configuration vs horizontal tail





- Advantage: canard increases the total lift
- Canard design is difficult
 - Stability requires $\Delta L'_z < \Delta L_z$ for $\Delta \theta > 0$
 - When flaps are down, this requires $\Delta L'_z > \Delta L_z$
 - Canard should stall before the wing
 - So the plane dives and its velocity increases
 - Use of the wing at maximum angle of attack is therefore forbidden
- Really useful with unstable design





• Advantage: canard increases the total lift



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- Stability requires $\Delta L'_Z < \Delta L_Z$ for $\Delta \theta > 0$
- When flaps are down, this requires $\Delta L'_Z > \Delta L_Z$
- Canard should stall before the wing
 - So the plane dives and its velocity increases
 - Control surfaces on the wing remain effective
 - Use of the wing at maximum angle of attack is therefore forbidden
- Over/under-pressure on in/extrados induce vortex at wing tips
 - (Lift) induced drag
 - Canard induces a downwash near wing roots and upwash near wing tips
 - Decreases wing efficiency and increases stall risk at wing tips
 - Reduces wing control surfaces efficiency
- Really useful with unstable design



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The advent of aviation

- The first airlines and airmail services
 - 1927, foundation of Pan Am
 - Airmail service to Cuba
 - Seaplanes
 - 1938, transatlantic airline (Boeing 314)
 - 1934, Air Mail Scandal



- 1925 (Kelly act), the US-post can contract with public (US meaning) companies
- Airmail subsidized per letter is junk mails
- 1930 (Hoover), subsidies for cargo capacity instead of cargo carried
 advent of passenger transport
- 1930, 3 accredited companies: TW&A, United (Boeing) & AA (conglomerate of 82 companies)
- 1934, allegation of collusion between the companies and the Roosevelt administration
 - Roosevelt
 - » Canceled the accreditations,
 - » Split the companies into manufacturers and transport companies
 - Boeing & United are distinct
 - The Army (Air Corps) is temporarily in charge of the airmail
 - » Poor infrastructures and no modern airplanes ____ numerous accidents
 - » New contracts with new companies





Solutions to pitch up

- Wing root has to stall first
 - Washout
 - Taper > 1 (XF91)
 - Prevent boundary layer separation at tips
 - Slats at tips (higher camber
 - → lower attack angle)
 - Vortex generation on the extrados
 - » vortilons (DC9, B717, Embraer), pylons
 - » Sawtooth (Super Etendard)
 - » Golf ball effect (Gloster Javelin)
 - Prevent root to tip flow
 - Wing fences (SU22)
 - Forward swept
 - » 1944, JU 287
 - » 1984, X29
 - » Unstable in yaw fly-by-wire









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Aircraft Design - Introduction & History

Boeing 727

• 1964

- Companies wanted to reduce the fuel consumption
 - Twinjet forbidden on roads further than
 60-minute flight from an airport (Caribbean)
 - Development of a three-engine airliner
 - P&W JT8
 - 62 kN
 - Low by-pass turbofan (0.96:1)
 - Noisy
 - 150 passengers
 - Introduction of an APU
 - Hydro mechanical commands
- Comparison
 - Consumption in g / Available Seat km
 - 727: 37
 - 707: 62









Buoyancy

- Balloons or non-powered aerostats (lighter than air)
 - 1783, France, Montgolfier brothers: first hot-air balloon
 - Believed that smoke was responsible for levity
 - Empty flight, then with animals at Versailles exhibition (Louis XVI)
 - Reached 300 m altitude



- Add a burner in order to gain autonomy
 - Flight of 8.5 km with two men on board (Rozier & Marquis d'Arlande)





Buoyancy

- Balloons or non-powered aerostats (lighter than air) (2)
 - 1783, Jacques Charles, France
 - Identified buoyancy (Archimede's principle)
 - Replaced hot-air by hydrogen
 - Flew 43 km

- 1861, USA
 - Used for military observation during civil war







- NB:1709, Bartholomeu Lourenço de Gusmão (Portugal)?
 - Sketch of a machine with hydrogen balloons



Airchips

- Airships or powered aerostats (lighter than air)
 - 1785, Blanchard, France
 - Crossed English Channel
 - Balloon using hydrogen
 - « Flapping wings » as propulsion means?
 - Ruder for lateral control (yaw)
 - Has parachute on board
 - 1852, Giffart, France
 - First steam-powered airship
 - 3-hp steam engine
 - 27-km long flight
 - Unable to flight against the wind
 - 1872, Dupuis de Lôme, France
 - First airship with, although limited, maneuverability
 - Order of the French army
 - Communication during the 70^s war
 - 8-person powered







Airchips

- Airships or powered aerostats
 - 1884, La France
 - First fully controllable flight
 - Order of the Army
 - 9-hp electric engine
 - 1900, von Zeppelin, Germany
 - First rigid structure
 - Improve maneuverability
 - 2x15-hp piston engines (36km/h)
 - Pitch controlled by a moving mass
 - 1908, passenger transport
 - Bombers during WWI
 - 1930, transatlantic transport
 - Hydrogen is too hazardous
 - Use of Helium
 - 1937, Hindenburg on fire
 - Use of hydrogen due to embargo
 - End of activities due to WWII
 - 1905, Louis Cartier, France
 - First wristwatch: his friend Santos-Dumont could use it during the flights







Aeronautics pioneers

- Aerodynes (heavier than air): First airplanes
 - 1842, Hanson & Stringfellow, UK
 - Aeriel Steam Carriage concept (too heavy)
 - Concept of
 - Lifting surfaces
 - Tails
 - Propulsion
 - 1848, Stringfellow, UK
 - First steamed powered flight
 - Unmanned airplane
 - ~1871, Alphonse Pénaud, France
 - Build toys
 - Roll stability: dihedral wing
 - Pitch stability: horizontal tail with negative angle of attack
 - Propulsion
 - 2-blade propeller
 - Powered by twisted rubber strands





First flights

- First success: the Wright brothers, USA (2)
 - 1904 flight (Flyer II)
 - 15-hp engine (catapulted at take off)
 - Suppressed the negative dihedral
 - Add weight under the canard (stability)
 - Reduced the camber of airfoils
 - Lower drag
 - 1-km long flight
 - Accomplished circles
 - 1905 flight (Flyer III)
 - 25-hp piston engine
 - 4-km long flight
 - Improved the stability by increasing the control surfaces
 - Roll and pitch controls dissociated
- 1906, Alberto Santos-Dumon, Brazil
 - Flight of the 14bis

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First controlled flights

- Louis Blériot, France
 - 1907, Blériot V
 - 5-m long flight
 - Monoplane with canard
 - « Wing warping » & elevators controlled by the "cloche" (to become the yoke, Esnault-Pelterie 1906)
 - 1907, Blériot VII
 - Successful U-turn
 - Monoplane with fixed wing (no control surfaces)
 - Elevators on horizontal tail can be deflected
 - Symmetrically (pitch)
 - Anti-symmetrically (roll)
 - The rudder is controlled by pedals





La cloche Blériot dans sa forme définitive.





Aircraft Design - Introduction & History



The advent of aviation

• WWI

- Use of bi or triplanes
 - Lower lift and higher drag than a wing of same total area
 - Simpler structure as the span is smaller (web structures with wood and fabric)
- 1915, Junkers prototype
 - Mid-wing monoplane
 - Achieved due to use of sheet steel
 - Aluminum alloy were too expensive
- 1915, Rolland Garros
 - Machinegun on aircraft nose
 - Armored propeller blades
 - No need for a gunner
- 1915, Garros' plane captured
 - Fokker: interrupted gear
 - Propeller and machineguns are synchronized









- The first airlines and airmail services (2)
 - 1918, France, first flights of the "aéropostale"
 - Toulouse Barcelona, and then to Casablanca & Dakar
 - To south America, transport by
 - Boat between Dakar and the Brazil
 - Airplanes between Brazil and Chile
 - 1930, Mermoz carried 122 kg of airmails
 - Between Dakar & Natal (Brazil)
 - Latécoère 28 (21-h flight)
 - Crashed on the way back





Aircraft Design - Introduction & History



Air supremacy became strategic
 Spitfire



- Rolls-Royce engine
 - Supercharged
 - Liquid-cooled
 - V12
 - 1400cv
 - Carburetor (deep dives forbidden)
- 600 km/h at 4000 m
- Ceiling 11000 m
- Rate of climb 13.5 m/s

Bf109 Messerschmitt



- Daimler-Benz engine
 - Supercharged
 - Liquid-cooled
 - Inverted V12
 - 1500cv
 - Direct fuel injection (allowed dives)
- 640 km/h at 6300 m
- Ceiling 12000 m
- Rate of climb 17 m/s





Toward high subsonic velocities

Compressibility effects

- 1941, accident of a P38 unable to recover from a dive
 - NACA build a Mach 0.75 full size wind tunnel
 - Above Mach 0.68 they found that
 - Lift moves backward on the wing
 - Wing lift decreases → less downwash → more lift on horizontal tail
 - Dive unrecoverable until reaching low altitude
 - Introduction

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- Limit airspeed vs altitude abacus 2901AS-440TAS
- Diving flaps (change center of pressure location)
- These compressibility effects were actually already known







Groundbreaking concepts during WWII: toward supersonic flights

The « sound barrier »

- End of the 30^s
 - Physics in transonic range is not known
 - Equations cannot be linearized
 - No computers
 - 1935, UK, Hilton explain to a journalist that drag increases in an unknown way close to Mach 1: this became the « sound barrier »
 - 1941, the P-38 accidents popularized the barrier hoax
- Early 40^s: Measure of transonic flow
 - 1941, USA, Mach 1 experiences in wind tunnel failed due to the shock reflections (solved in 48 by adding holes in the walls)
 - 1944, scaled models were attached on a P-51 wing
 - During dive at Mach 0.81 the flow on the extrados reached locally Mach 1.4







Groundbreaking concepts during WWII: Propulsion

- Above 700 km/h propellers are inefficient (2)
 - 1941-1944 Messerschmitt Me 262 (2)
 - 2 Junkers Jumo 004 engines
 - First axial turbojet
 - Thrust: 8800 N (each)
 - Compression ratio: 3.14
 - Diesel
 - 870 km/h (Mach 0.7) at 6000 m
 - Ceiling: 11000 m
 - No anti-G suit
 - Too fast for machinegun to be used
 rockets R4m
 - Similar aircrafts
 - UK: Gloster Meteor
 - US: P59







Aircraft Design - Introduction & History



- Tailless aircrafts (2)
 - Longitudinal stability
 - Lift backward of CG
 - Longitudinal equilibrium
 - As lift is backward of CG
 - Wing should produce a positive (nose up) moment
 - Cambered airfoils produce negative moment
 - So how to reach the equilibrium?
 - Reflex airfoils
 - » Negative camber at the trailing edge
 - » Solar Pathfinder
 - Swept wing with tips at negative angle of attack
 - » Horten IV
 - Elevons deflection
 - These devices increase the drag
 - No high lift devices
 - As they produce a negative moment







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- Tailless aircraft: flying wing
 - 1944
 - The Me 262 cannot reach London (Fuel consumption of the Jumo 004 is too high)
 - The Horten brothers want to remove fuselage & tail in order to reduce the drag
 - Ho 229 derived from the glider Ho II
 - Glider & prototype build
 - Version 3 captured by the USA
 - 1947, Northop YB49, USA
 - Low critical Mach number (thick airfoil)
 - Not stable enough to be used as a bomber







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- Tailless aircraft: flying wing (2)
 - 1989, B-2 spirit
 - Stealth: a flying wing has a low Radar Cross Section
 - Stability possible with fly-by-wire control
 - Velocity: 760 km/h





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- Tailless aircraft: swept wing
 - 1941, Me 163
 - Short swept wing
 - Rocket engine
 - Slots at leading edges
 - Air from below accelerates through the slot towards above the wing
 - This high-speed flow delays boundary layer separation
 - Decrease stall speed
 - Make spin impossible
 - Too fast for
 - Machineguns required skill
 - Only a few successful shootings
 - 8-minute long flights
 - Velocity of 1004 km/h
 - Ejection seat







- Tailless aircraft: Δ wing
 - 1944, Lippisch P13a
 - Experiments in wind tunnels:
 - Stable until Mach 2.6
 - Glider prototype (DM1)
 - Captured by the USA
 - Ramjet (coal dust)
 - 1948, Lippisch worked for Convair
 - Prototype Convair XF92
 - Yeager flew at Mach 1.04
 - Landed with
 - A high angle of attack
 - A low velocity (100 km/h)







Swept wing

- 1935, Volta conference
 - Busemann, Germany pioneered the concept of swept wing
 - Normal Mach number lower than aircraft Mach number
 - 1945, Jones drew the same conclusions (US)
- 1944, Me P1011

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- Wing with sweep angle of 30, 40 or 45° (to be changed on the ground)
- Research on swept angle effect
- Prototype captured and sent to Bell











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• Swept wing

- 1944, Sabre F86
 - Order of the Air Force for a transonic turbojet
 - Original design inspired from the XFJ-1
 - Order of the Navy
 - Critical Mach was too low and the original design did not respect the Air Force requirements







• Swept wing (2)

- 1944, Me P1011
 - Wing with sweep angle of 30, 40 or 45°
 - (to be changed on the ground)
- 1944, Sabre F86
 - Original design failed due to the unswept wing
 - 1947, Prototype XP86
 - Swept wing (35°)
 - Automatic slats of the Me262
 - Symmetric airfoil (uncambered)
 - Pressurized cockpit
 - 1948, sound barrier broken during dive
 - Turbojet
 - GE J47

1953, Mach 1.05

- Thrust: 23 kN
- Hydromechanical Controls
- Super Sabre F 100





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Volume drag

- Area rule, Whitcomb, NACA
 - 1943, Junker already applied it
 - For supersonic flow there is a drag depending on the volume
 - ~1950, Sears-Haack, volume drag minimum for r/r0=(1-x²)^{3/2}
 - ~ Mach 1: volume drag is similar to the body of revolution with the same cross-sectional areas
 - M > 1: one has to consider the area along the Mach cone (and not cross-sectional)







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Supersonic military aircrafts

- Volume drag (2)
 - 1953,
 Convair YF 102
 - Original design unable to reach Mach 1
 - Design correction
 - Coke bottle
 - Called in
 France
 "taille de
 guêpe"
 - Nowadays,
 engines have
 enough thrust
 - Cabin design for transport aircraft would be too complex







Modern airliners

- 1952, De Havilland 106 Comet 1, UK (2)
 - More design issues
 - 1954, January, flight BOAC 781 Rome-Heathrow
 - Plane G-ALYP disintegrated above the sea
 - After 1300 flights
 - Autopsies of passengers' lungs revealed explosive decompression
 - Bomb? Turbine failure ?
 - \implies turbine rings with armor plates
 - 1954, April, flight SAA 201 Rome-Cairo
 - Plane G-ALYY disintegrated
 - 1954, April, reconstruction of plane ALYP from the recovered wreckages
 - Proof of fracture, but origin unknown
 - 1954, April, test of fuselage ALYU in water tank
 - Pressurization cycles of the cabin simulated
 - Rupture at port window after only 3057 pressurization cycles well before the design limit of 10000 cycles







~1955, there had been a market for SST (2)

- Le Concorde
 - Engines are efficient at super-cruise
 - Olympus RR/Snecma turbojets
 - » Afterburner only in transonic
 - Inefficient at lower velocity
 - Ogival Δ wing inefficient at low velocity
 - 1971, Supersonic regime was authorized only above ocean Le Concorde was no longer profitable
 - Tickets price just allowed to pay operation costs but not development costs
- 2000, accident during take off
 - Tire exploded after rolling on a wreckage
 - A piece of rubber hit the fuel tank and broke an electrical cable
 - Shockwave in the fuel tank caused a leak
 - Leaking fuel ignited due to severed electrical cable
- 2003, economic crisis le Concorde is removed from service







Supersonic transports (SST)

• ~1955, there had been a market for SST (3)

- 1964, USA asked for proposals
 - 2 projects
 - L2000 (Lockheed)
 - B 2707 (Boeing)
 - » Initially with variable geometry
 - B 2707 is selected
 - Variable geometry was too heavy
 - Became a Δ wing
 - 1971, Supersonic regime was authorized only above ocean
 - they stopped the development
- 1963, Tu-144 (Russia)
 - 1969, First supersonic flight
 - 1973, crash at Paris (Mirage ?)
 - 1975, used for mail services
 - 1977, passenger transport
 - 1978, accident & end of services
 - Required afterburner in super-cruise
 - Canard (positive moment without reducing lift as when acting on the elevons)





