Aircraft Design
Introduction to Conceptual Design & Aviation History

Ludovic Noels

Computational & Multiscale Mechanics of Materials – CM3
http://www.ltas-cm3.ulg.ac.be/
Chemin des Chevreuils 1, B4000 Liège
L.Noels@ulg.ac.be
Goals of the classes

• 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, …. 
Goals of the classes

- How do we want to design?
  - Requirements depend on the aircraft finality

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<td>• Low noise desirable</td>
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2013-2014 Aircraft Design - Introduction & History
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
Goals of the classes

• 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
First attempts

- Hot air balloons (China, 2\textsuperscript{nd}-3\textsuperscript{rd} century, military signaling)
- Marco Polo (13\textsuperscript{th} century) kites are used in order to lift humans
- First wings
  - Icarus & Dedalus
  - Abbas Ibn Firnas (9\textsuperscript{th} century, Spain)
  - Eilmer of Malmesbury (11\textsuperscript{th} century, England)
  - These two jumps failed (although the jumpers survive) due to the lack of stability (no tails)
    - 2008, Yves Rossy flew with rocketed wing
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
From birds to planes

- The ornithopter (2)
  - 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
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

- **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 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
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

- **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
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**
  - 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
First controlled flights

- **Louis Blériot, France (2)**
  - 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)
The advent of aviation

- **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 advent of aviation

- **WWI (2)**
  - 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 advent of aviation

- The first airlines and airmail services (1)
  - 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
The advent of aviation

• 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
The advent of aviation

- 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
The advent of aviation

- 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 advent of aviation

- **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)
The advent of aviation

- **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
WWII

- 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 high velocity
• **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)
Air supremacy became strategic (3)

**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

- 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 Dr1)
    - 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”
Toward high subsonic velocities

- 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 an hydraulic one
    - Artificial feel devices
      - Avoid overstressing the structure
      - Springs, bob-weight, stick shaker, …
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 → series of increasing overcorrections in opposite directions
Compressibility effects

- 1887, Austria
  - Mach took a picture of a supersonic flow
- ~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
- 1935, Volta conference
  - Busemann, Germany pioneered the concept of swept wing
  - Normal Mach number lower than aircraft Mach number
- Spitfire with thin airfoils
  - Higher critical Mach
  - But low torsional stiffness
  - Risk of aileron reversal
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

- Above 700 km/h propellers are inefficient (3)
  - 1944, Germany, pulse jet engine
    - Cheap and easy to produce
    - Prototype on Me 328
    - V1 (630 km/h at 900 m)
    - Works at zero velocity
    - Non continuous thrust
  - Rocket engine, Germany
    - 1941, Me163
  - November 1944, V2
    - Mach 4
    - Altitude: 100 km
Groundbreaking concepts during WWII: Propulsion

- Above 700 km/h propellers are inefficient (4)
  - 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 30s
    - 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 40s: 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: toward supersonic flights

• The « sound barrier » (2)
  – 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: aerodynamics

- **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)

- **The wing has elevons**
  - 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
Groundbreaking concepts during WWII: aerodynamics

- **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
        - underpressure
        - lift
      - Maneuverability at low velocity
    - **Simple and robust structure**
  - **Drawback:** low aspect-ratio
    - induced drag
Groundbreaking concepts during WWII: aerodynamics

- **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
Groundbreaking concepts during WWII: aerodynamics

- **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
Groundbreaking concepts during WWII: aerodynamics

- **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
      - Thrust: 23 kN
  - Hydromechanical Controls
    - Super Sabre F 100
      - 1953, Mach 1.05
Groundbreaking concepts during WWII: aerodynamics

• **Pitch up or Sabre 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
Groundbreaking concepts during WWII: aerodynamics

- **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 \(\rightarrow\) 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)
Groundbreaking concepts during WWII: aerodynamics

- **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 → 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
• 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
Modern airliners

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?
• 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?
      → 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
Modern airliners

• 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
Modern airliners

- **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
Modern airliners

- **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
Modern airliners

• 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)
Modern airliners

- 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 reaching divergence Mach)
Modern airliners

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

- Since the mid-70s
  - Used on civil airliners
    - A300, B767, B777, ERJ 145 …
• **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
Modern airliners

• 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
Modern airliners

- **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 €

Modern airliners

- **Airbus (subsidies) VS Boeing (public) (2)**
  - Most recent airliners
    - **B787**
      - 250-passenger twinjet
      - $150 millions
      - 787 concept
        - -20% fuel consumption
          - was 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 passengers twinjet
      - 52% structural weight in composite
Supersonic transports (SST)

- ~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 Transport](image-url)
Supersonic transports (SST)

• ~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)
Near future

• **Air traffic evolution**
  - Airbus estimations for 2026
    • Revenue Passenger km: x2
    • Cargo transport: x3
    • 23000 new aircrafts will be required only for passenger transport
      - Mainly for Asia

**20 year demand for 23,385 passenger aircraft worth US$2.6 trillion**

<table>
<thead>
<tr>
<th>Number of new aircraft</th>
<th>Percentage</th>
<th>Price (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-aisle</td>
<td>71%</td>
<td>43%</td>
</tr>
<tr>
<td>Small twin-aisle</td>
<td>17%</td>
<td>27%</td>
</tr>
<tr>
<td>Intermediate twin-aisle</td>
<td>7%</td>
<td>14%</td>
</tr>
<tr>
<td>Very large aircraft</td>
<td>5%</td>
<td>16%</td>
</tr>
</tbody>
</table>

Passenger aircraft >100 seats (excluding freighters)

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**Freight traffic to triple in twenty years**

AAGR: Annual Average Growth Rate
* FTKs: Freight Tonne Kilometres

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Near future

**Next aircraft generation?**
- During the last 35 years
  - Aircrafts look the same
  - Operation costs have been reduced by 3
- During the next following years
  - Fuel consumption should be reduced by 70 %
    - Active control (10%)
      » Smaller stabilizing surfaces
    - Airflow control (wing & fuselage) (10%)
      » Lower drag
    - New materials (20%)
    - Propulsion (20%)
      » More efficient turbines
    - Multidisciplinary optimization (10%)
      » The use of a new technology requires a total redesign of the aircraft to be fully exploited
  - Supersonic business jets ?
References

- **Reference of the classes**

- **Others**
  - **On-line**
    - Introduction to the aerodynamics of flights, SP-367, NASA Langley research center, [http://history.nasa.gov/SP-367/contents.htm](http://history.nasa.gov/SP-367/contents.htm)
    - Dryden Flight Research Center, [http://www.nasa.gov/centers/dryden/home/index.html](http://www.nasa.gov/centers/dryden/home/index.html)
    - [http://www.centennialofflight.gov/essay_cat/re_category.htm](http://www.centennialofflight.gov/essay_cat/re_category.htm)

  - **Books**
Annex 1: 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
Annex 1: 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: $Re = \frac{UL}{\nu}$ constant
• **Advantage:** canard increases the total lift

![Diagram](image)

• **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
    - 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**
Annex 3: The advent of aviation

• The first airlines and airmail services (4)
  – 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 ➞ 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
Annex 4: 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 \(\rightarrow\) 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 \(\rightarrow\) fly-by-wire
Annex 5: 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
Annex 6: 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
Annex 7: 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 70s war
    • 8-person powered
Annex 8: 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 Pénau, 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
Annex 9: 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-Dumont, Brazil**
  - Flight of the 14bis
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
• **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 \( \rightarrow \) less downwash \( \rightarrow \) more lift on horizontal tail
    - Dive unrecoverable until reaching low altitude
  - Introduction
    - Limit airspeed vs altitude abacus
    - Diving flaps (change center of pressure location)
  - These compressibility effects were actually already known
Annex 12: 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

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Annex 12: Groundbreaking concepts during WWII: aerodynamics

- **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
Annex 12: Groundbreaking concepts during WWII: aerodynamics

- **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
Annex 12: Groundbreaking concepts during WWII: aerodynamics

• **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
Annex 12: Groundbreaking concepts during WWII: aerodynamics

- **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
Annex 12: Groundbreaking concepts during WWII: aerodynamics

- **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)
Annex 12: Groundbreaking concepts during WWII: aerodynamics

- **Swept wing (2)**
  - 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
    - 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
Annex 13: Supersonic military aircrafts

• 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 $r/r_0=(1-x^2)^{3/2}$
      – ~ 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)
Annex 13: 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