Aircraft Configurations

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Learning Outcomes

- Identify the most popular fixed wing aircraft configurations
- Understand, at a high-level, the main benefits/drawbacks of the various configurations
- Rudimentary understanding of longitudinal trim/stability of fixed wing aircraft
- Understand trade-off between inherent stability and feedback control stabilization

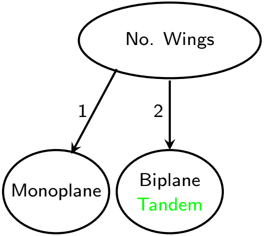
Fixed Wing Aircraft Configurations

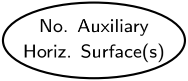
No. Wings

No. Auxiliary Horiz. Surface(s)

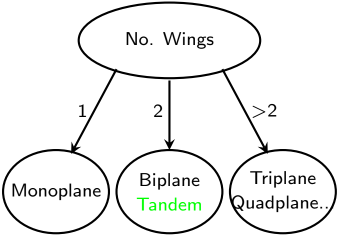
Fixed Wing Aircraft Configurations

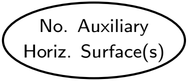
Fixed Wing Aircraft Configurations





Fixed Wing Aircraft Configurations





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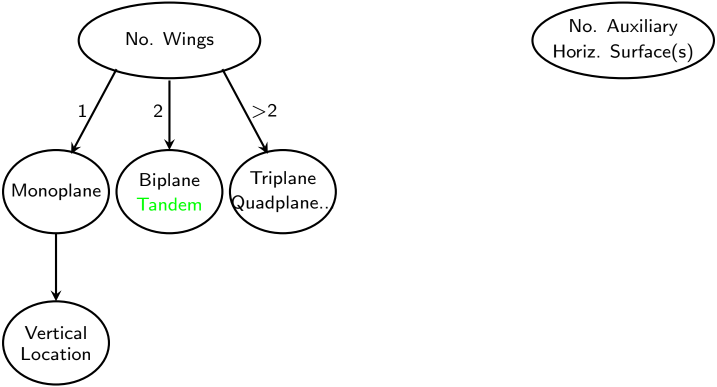

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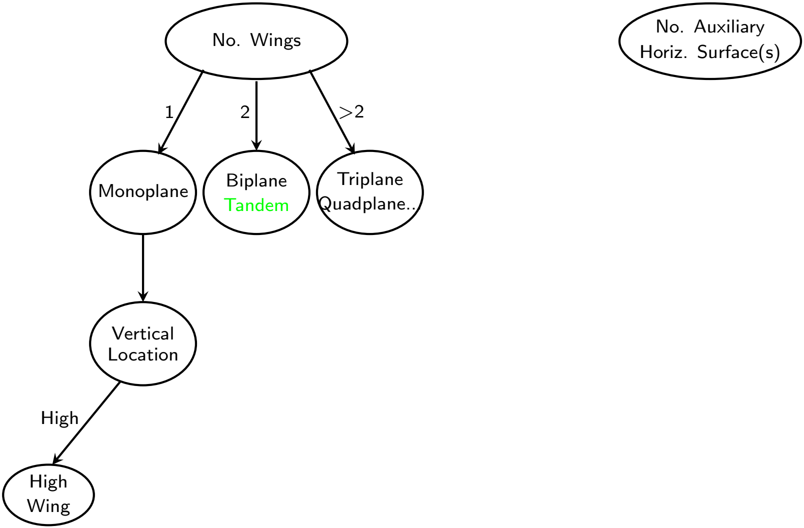

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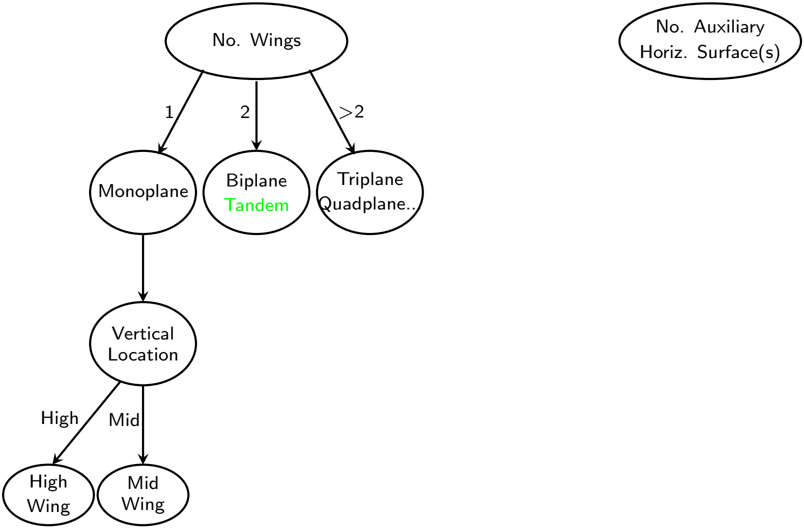

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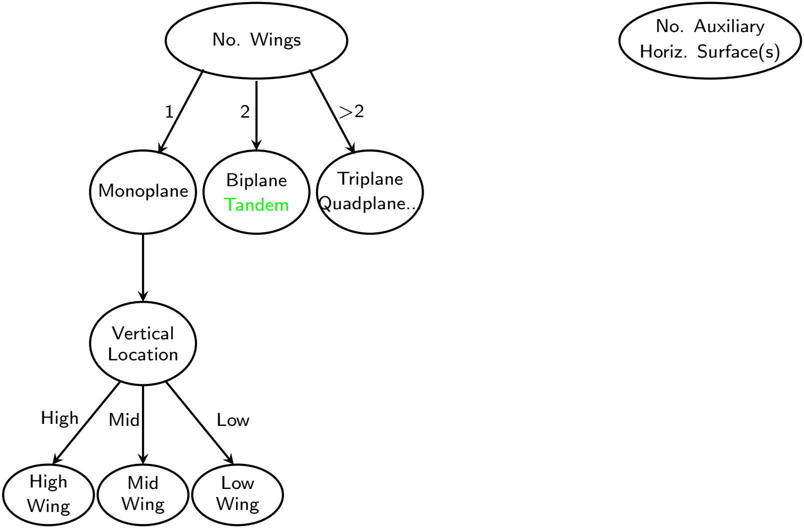

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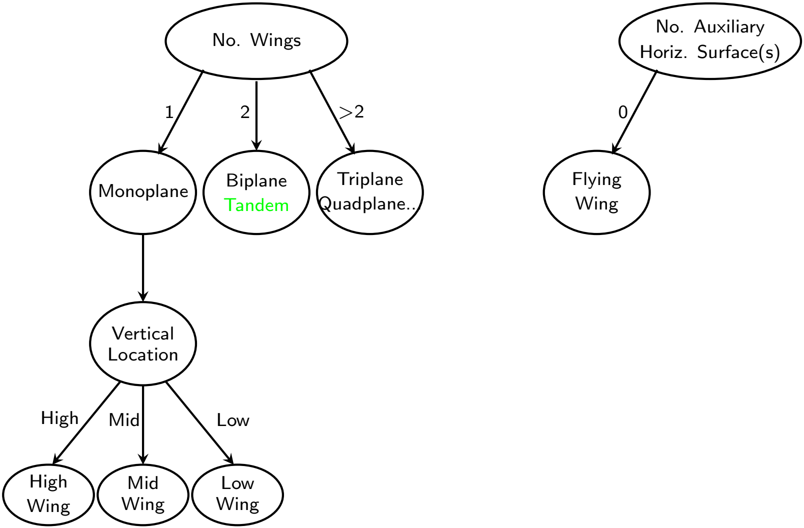

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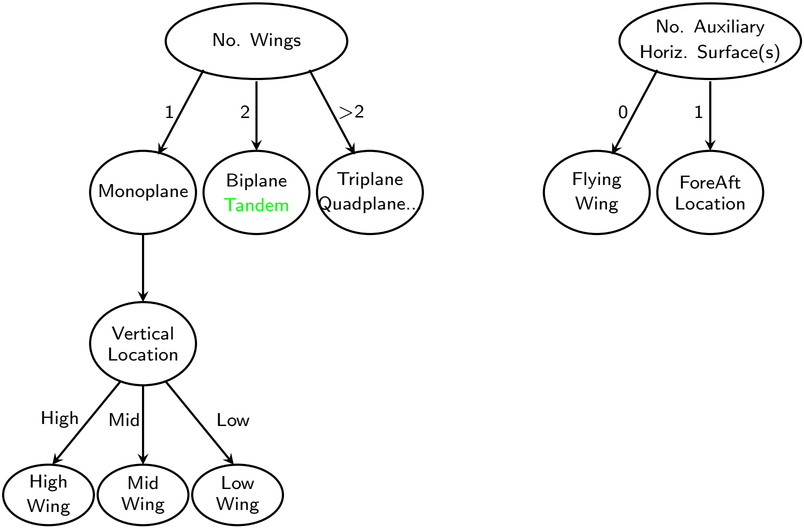

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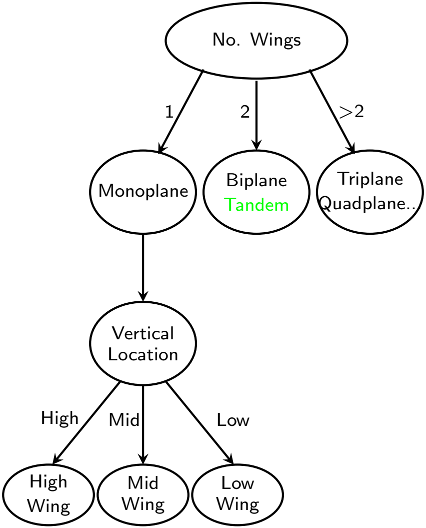

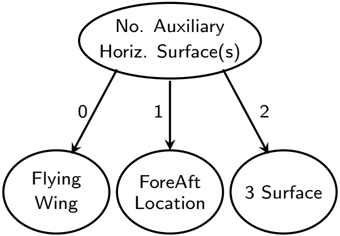

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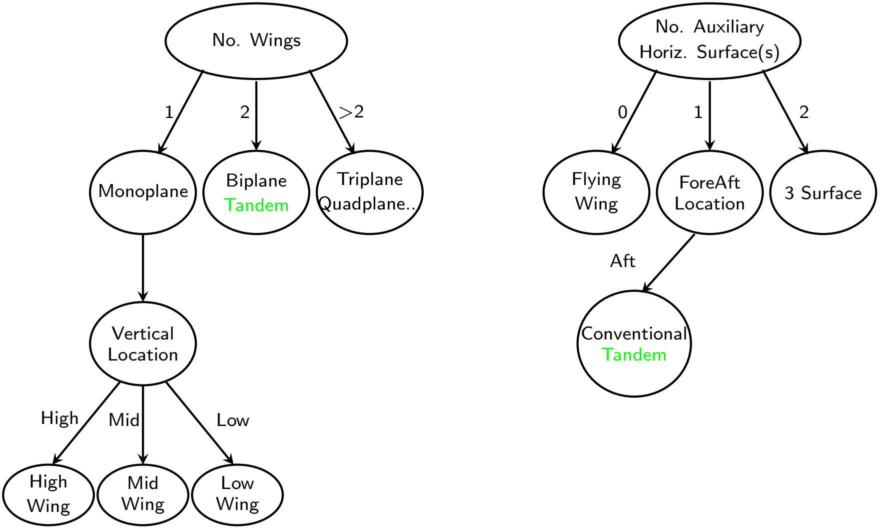

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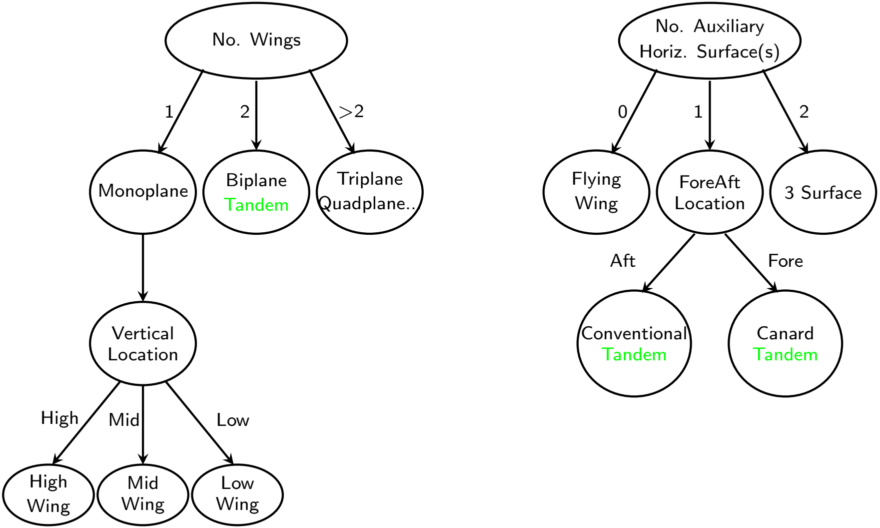

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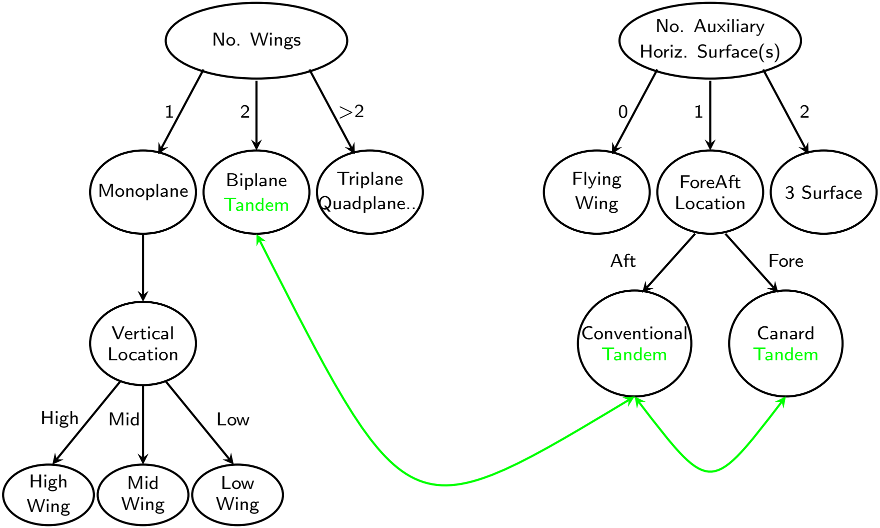


Conventional

Conventional *Monoplane* High-Wing

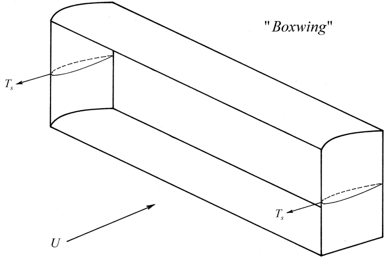
Conventional *Monoplane* Low-Wing

Flying Wing

Monoplane Flying Wing

Biplane/Box-wing

Conventional Biplane (Queen Bee)



Boxwing

Canard/Tandam

Canard *Monoplane*

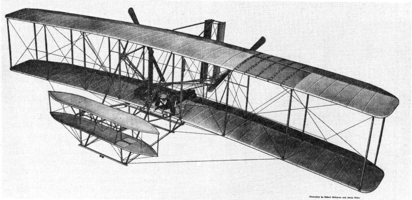
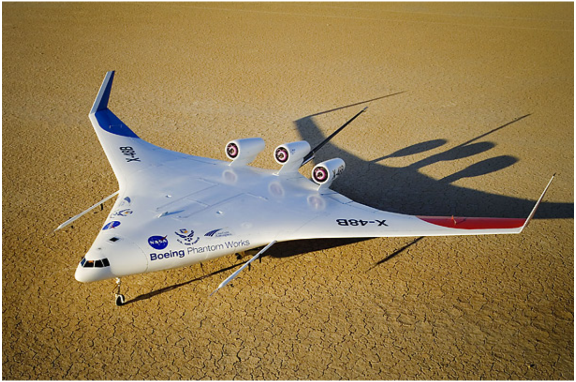


Illustration of the 1903 Wright Flyer by Robert McLarren and James Fisher.

Canard Biplane

Blended Wing-Body, BWB



Monoplane Flying Wing–X48-B Blended Wing Body (BWB)

Why Do Aircraft Look the Way They Do?

- Aircraft come in wide variety of shapes
  - depends on payload, objectives and many different constraints

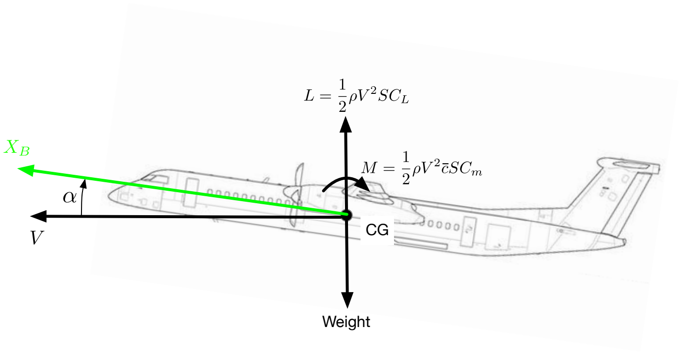
Civil Aviation

- Cost of accident very high
- Inherent stability and good Handling Qualities (HQ) usually sought
- Limiting factor for civil aviation design often penalty associated with trim, stability and handling
  - Stability, trim, HQ determined by layout and size/placement of stabilizing surfaces
  - Strict rules regarding full-authority feedback control for stabilization
    - cost of certification extremely high, civil aviation typically stable or very close to stable

UAV's (+ other aircraft)

- Cost of accident is usually much lower $\rightarrow$ inherent stability not necessarily required
- New control methods allow for configurations that would otherwise be impossible to fly
- Still important to understand trim, stability and HQ so informed trade-offs can be made

Steady Level *Trimmed* Flight

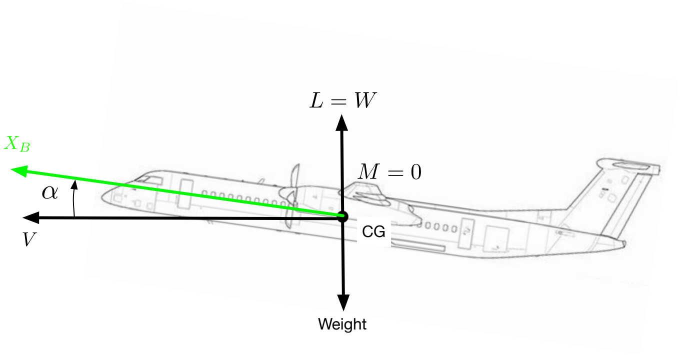


- For Steady, Level Flight (ignore T and D for now):

$$
\begin{aligned}
L &= W \quad \rightarrow \quad C_L = \frac{2W}{\rho V^2 S} \\
M &= 0 \quad \rightarrow \quad C_m = 0
\end{aligned}
$$

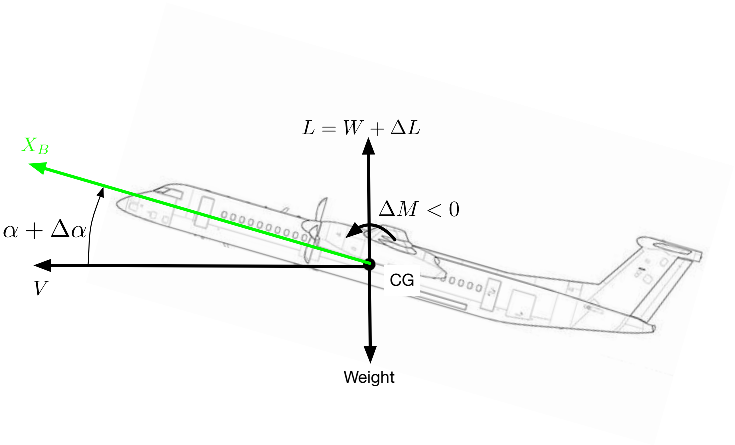
- Nose-up $\rightarrow +$ve M
- Trimmed Flight $\rightarrow$ equillibrium$\rightarrow$ sum of forces and moments is zero

Pitch Stability



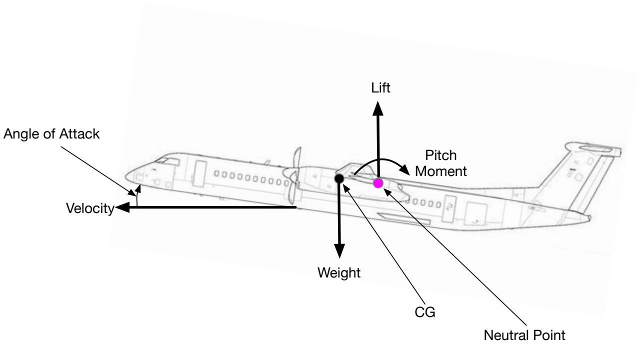
Aircraft Flying Along in Equilibrium (Trim)

Pitch Stability



Aircraft Disturbed by Gust, $\Delta M/\Delta\alpha < 0$ for Static Stability

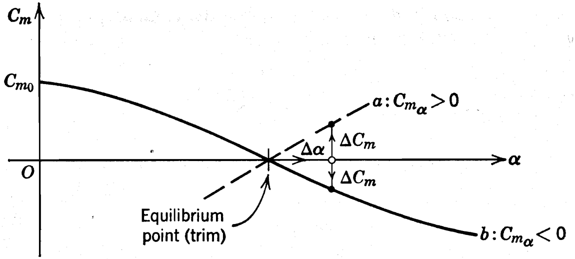
Pitch Stability



- Aircraft has Neutral Point (NP) which is like aerodynamic center for entire aircraft
  - $C_{m_{NP}}$ constant, does NOT change with α
- Thus if CG in front of NP aircraft is statically stable!

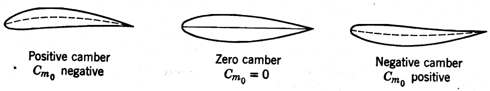
Review of Longitudinal Static Stability&Trim

- For equilibrium flight must have total forces and moments zero
- For longitudinal trim (balance) this means $L = W$ and $T = D$ and $C_m = 0$
- For static stability must have $\partial C_m / \partial \alpha < 0$ (restoring moment for disturbance)

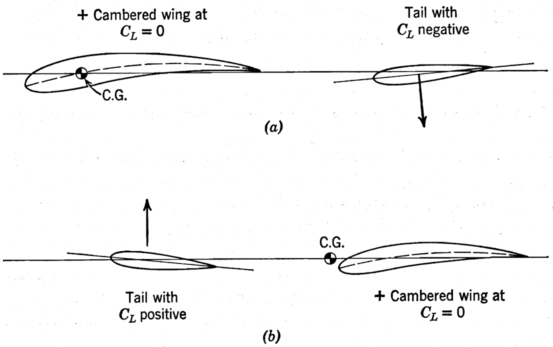


- $\partial C_m / \partial \alpha < 0$ can almost always be achieved by moving CG forward
- $\partial C_m / \partial \alpha < 0$ implies $C_{m_0} > 0$ for balance

- Most efficient lifting airfoils have positive camber $\rightarrow \quad C_{m_{ac}} < 0$



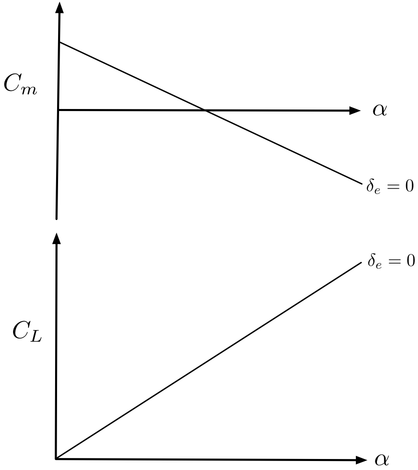
- Therefore, auxiliary surface often required for positive camber airfoil



- Flying Wings require reflex airfoil or other way to achieve $C_{m_0} > 0$ if inherent stability desired

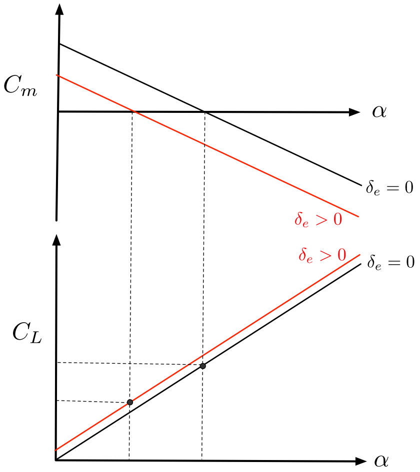
Conventional Trim

- Consider idealized C_m and C_L curve for conventional aircraft the "bare airframe"
  - 1 trim point, one α which means one V as L=W so $W = 1/2\rho V^2 SC_L$

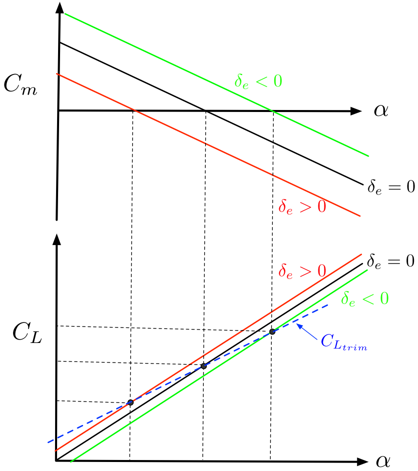


Conventional Trim

- Now shift C_m curve due to downward (i.e. +ve) elevator deflection (causes nose down moment), and accompanying small shift in C_L (downward elevator produces more lift)



Conventional Trim



Conventional Aircraft

- Tail connected aft of main wing by fuselage, is “conventional” for several reasons:
  - can easily be made stable (NP behind main wing AC thus easy to get CG infront)
  - can trim with almost zero tail load and thus a very small trim drag penalty
  - *CG* placement and trim is forgiving as elevator has plenty of authority in both directions before stalling
  - *CG* ends up within chord of wing thus fuel and payload can be easily added without changing *CG*
  - long fuselage gives good control authority with relatively small control surfaces

Canard Aircraft

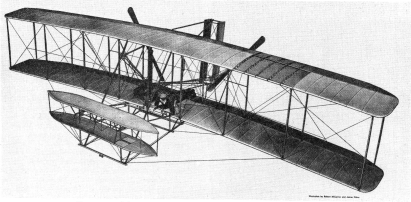
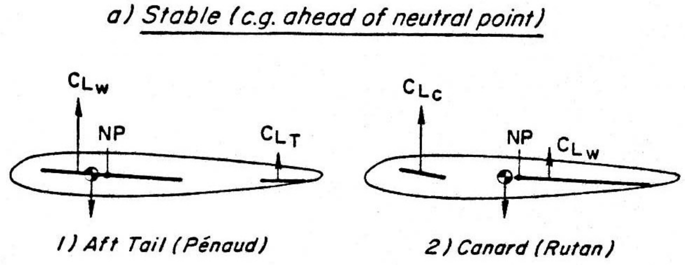


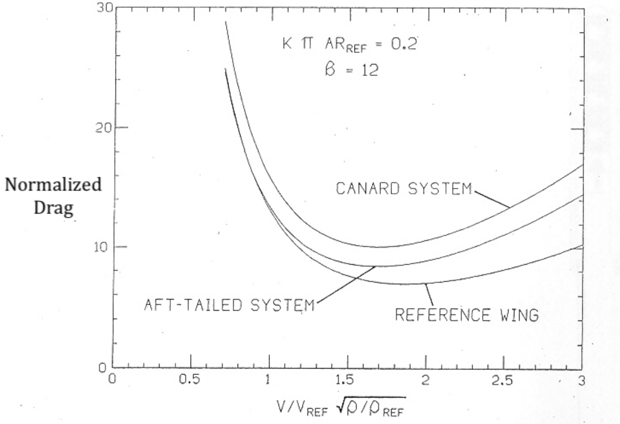
Illustration of the 1903 Wright Flyer by Robert McLarren and James Fisher.

- Canard configurations, with horizontal stabilizer forward of main wing, have existed throughout history
  - Wright Brothers used a canard for pitch control and as crash bumper
- Canards often have rear-mounted engines as seen in both aircraft–further aft NP makes possible
- Modern canard designers claim performance advantages in terms of stall characteristics and manoeuvrability
  - studies however, have shown overall performance generally reduced due canard downwash acting on main wing and increased trim drag

Stability and Trim Drag

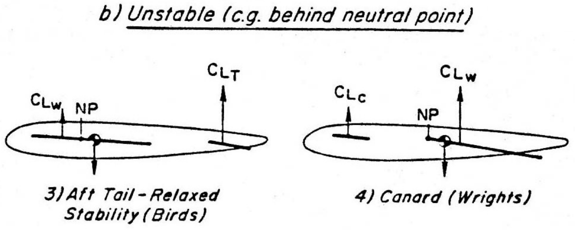


- Primary aerodynamic limitation of canard aircraft comes from stability requirement
  - for mass centre forward of neutral point, canard operates at higher lift coefficient than wing
  - if wing at optimal lift coefficient, canard is at higher non-optimal lift coefficient increasing induced drag of canard (trim drag)
  - tail-aft designs can have tail with close to zero lift coefficient
    - Tail often pulls down, but **not** necessary



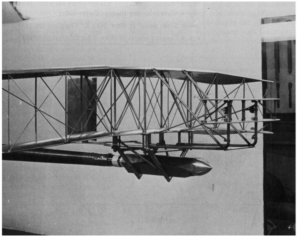
- McGeer and Kroo (1983 Journal of aircraft) performed efficiency comparison of canard and conventional with stability and trim requirements imposed
  - inferiority of two-surface systems over reference wing price of stability and control
  - for both fixed span and weight, conventional comes out ahead of canard

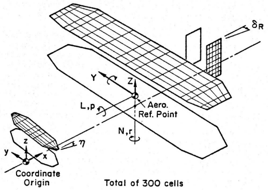
Relaxed Stability



- Aerodynamic efficiency of canards can be increased by relaxing stability requirement
  - i.e. allow mass centre to move aft of neutral point
- Wing and canard can then operate at their optimum lift coefficients
  - can increase efficiency of a conventional design in similar way, but not to same extent

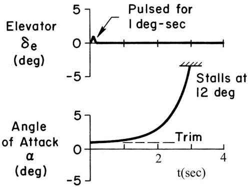
Wright Flyer





Approximation to the Wright Flyer
for Vortex Lattice Calculations

- Extensive analysis by National Air and Space Museum in 1980's confirmed Wright Flyer was highly unstable longitudinally



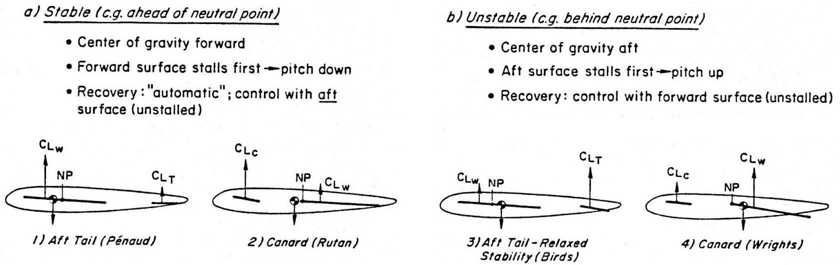
- Figure above shows response to a one-degree control blip
  - aircraft diverges to stall in 3 seconds

- Dynamic instability of the Wright Flyer overcome by considerable skill of the Wright Brothers
  - their subsequent design were somewhat less unstable
- Most aircraft since Wright Flyer have sought inherent stability
- However, computerized Stability Augmentation Systems (SAS) allow modern unstable canards to fly successfully

- X-29 experimental airplane, above, is example of SAS canard
- Trim drag issue much less severe at low lift coefficients
  - thus high speed canards more comparable to conventional designs

Stall Characteristics

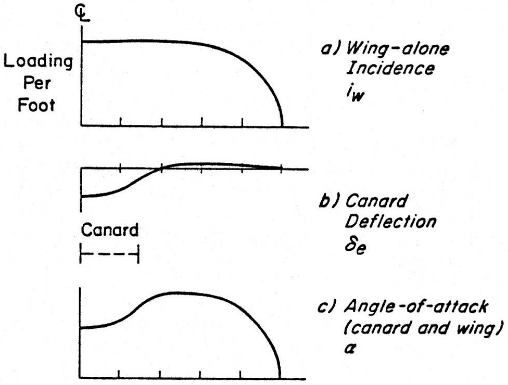
- Often claimed advantage of the canard design is “stall proof”
  - High AR and high C_L ensures canard stalls before main wing
    - nose will dip down and stall recovery has minimal altitude loss
    - control surface stalls so main wing stall impossible, lift maintained
- Tail on conventional typically has sufficient control to stall main wing



- Unstable canards–called Control Canard
- Stable canards–called Lifting Canard

Downwash

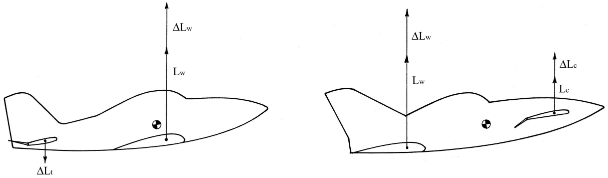
- Lift of main wing is diminished by downwash from canard



- This can significantly reduce wing's efficiency
  - spanwise loading varies from the minimum induced drag elliptical loading (unless compensated for)
  - downwash also tilts main wing's lift vector rearwards, adding additional induced drag

Maneuverability

- Canard configuration has maneuverability advantages



- Tail-aft airplane increases lift by first producing down force at tail
  - causes a nose-up pitch, thus increasing the wing lift beyond downforce of tail to give a net increase in lift
- Canard surface produces the initial force in desired direction giving faster pitch response
- At low speeds, however, lifting canard is operating at high lift coefficient may not have much authority before stalling
  - pitch-up at take-off may be difficult
  - high-lift devices on main wing generally not possible

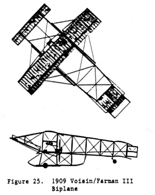
Engine and Fuel Placement

- Canard can accommodate rearward-mounted engine since neutral point further aft
  - Reduces slipstream effects on the wing
- Fuel placement for canard can be a problem
  - conventional aircraft typically has *CG* within chord of wing
    - wing can be filled with fuel without affecting stability
  - canard *CG* location not within wing

  - Defiant and Voyager, above, use counter-rotating front and rear props
  - fuel for Voyager's round-the-world journey is stored in two large vessels to sides of main fuselage

Three-Surface Designs

- 3 horizontal surfaces: benefits of canard with reduced trim drag



1909 Voisin/Farman

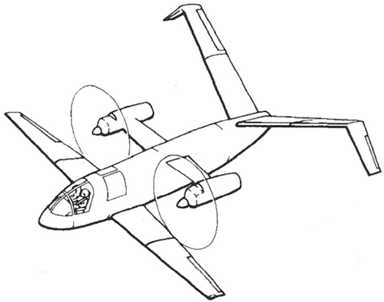
Piaggio

- Kendall 1984, *Performance Trades of Two-Surface and Three-Surface Configurations* concluded:
  - two-surface aircraft cannot have min induced drag at all CG locations
  - pure canards cannot have min induced drag, trim and static stability
  - three-surface designs can be stable and operate at min induced drag at all CG locations
- Did not consider extra friction/interference drag or structural weight

Tandem Wing

- When canard area approaches wing area, airplane known as "Tandem" configuration
- Offer induced drag reduction for given span and area
    - For same total wing area and span, AR reduced by 2 compared to monoplane$\rightarrow$ reduced induced drag
- Ability to shift neutral point by chord manipulation
- Not common; do not offer 100% advantage of tail-aft or canard
    - Extra drag due to downwash of first wing tilting lift vector of 2nd wing backwards
    - Difficult to make statically stable due to downwash

- Vought Aircraft proposed a tandem-wing configuration for VSTOL aircraft requiring long range and endurance (1978)
  - vehicle had wings of equal span
  - wing tips separated by a large vertical gap



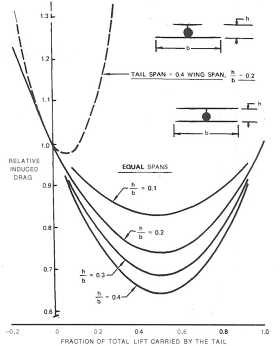
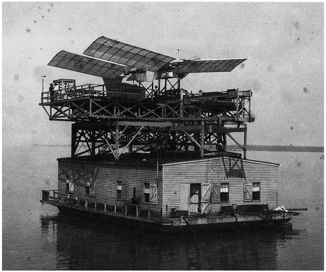
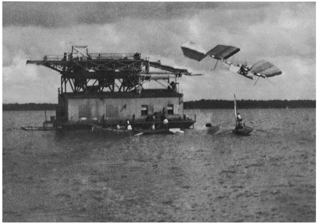
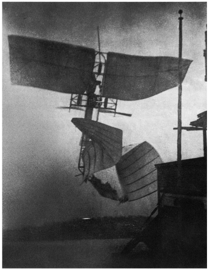


Fig. 1 Induced drag for tandem-wing and conventional wing-tail arrangements with optimal span-loadings.

- Figure shows reduction in induced drag for a fixed span over a conventional configuration
- Figure also compares various vertical spacings of wing, which affects amount of downwash rear wing experiences (destabilizing)

- Langley's series of tandem-wing "Aerodromes" in 1890's were very nearly first successful, powered aircraft
- Steam-powered model achieved successful uncontrolled flight, catapult launched from a houseboat over the Potomac

- Work culminated in piloted 1903 "Great Aerodrome",
  - failed on both attempts due to aero-elastic divergence of the wings
  - though bracing wires provide required bending strength, the slender wooden spars were highly flexible in torsion

Biplane

- Wright Flyer stacked two wings vertically rather than fore-aft like tandem
  - enormous structural advantage compared to tandem
  - biplane offers reduction in induced drag for a given span, or allows for reduction in span and rolling inertia for given induced drag
  - mutual interference reduces induced drag advantage

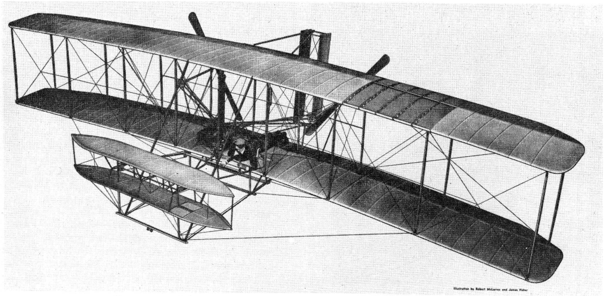
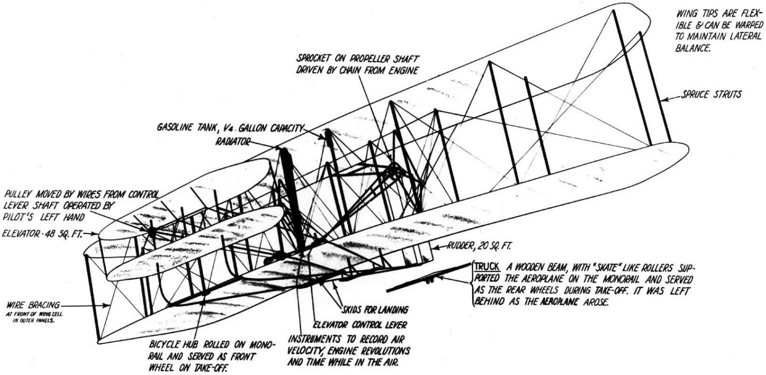


Illustration of the 1903 Wright Flyer by Robert McLarren and James Fisher.

- Visibility, structural complexity must also be considered when choosing to build biplane

Wing Structure

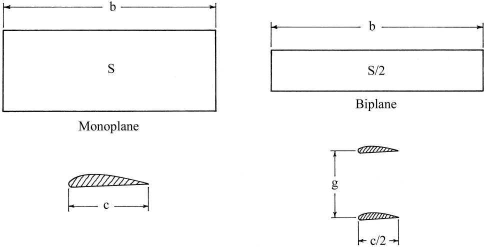
- Main structural advantage is wings of biplane act as top and bottom of deep trussed beam
  - $I = \frac{bh^3}{12}$, so added depth gives enormous weight savings
- Pioneering aircraft also used cross-bracing on front and rear of wing
  - creates large torsional box $\rightarrow$ large torsional stiffness
- Primary loads on spars are axial, instead of bending and twisting



- Thicker airfoils and higher speeds in later biplanes favoured removal of the outer bracing wires, added full torsion box
  - Such as Fokker D-7 shown below

Induced Drag Reduction

- Biplanes persisted beyond structural considerations because, for fixed span, they offer reduction in induced drag
- Consider the case below: a monoplane wing of area S and span b is split into a biplane, effectively doubling the aspect ratio.



- If wings are sufficiently far apart (i.e. no interference), induced drag for an elliptic lift distribution is given by

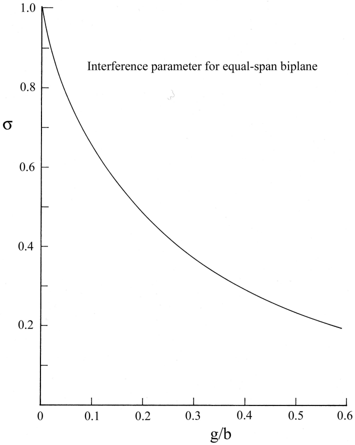
$$(C_{D_i})_{biplane} = \frac{C_L^2}{\pi AR_{biplane}} = \frac{C_L^2}{2\pi AR_{mono}} = \frac{(C_{D_i})_{mono}}{2}$$

- This is half that of the monoplane

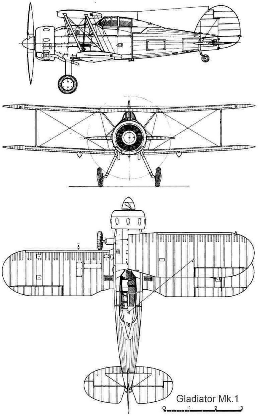
- In practice, mutual interference between wings limits induced drag savings
- Hiscock's interference parameter σ depends on vertical gap between wings.
- For wings with equal lift coefficients the induced drag is,

$$C_{D_i} = (1+\sigma)\frac{C_L^2}{\pi AR}$$

- approaches the monoplane as gap approaches zero



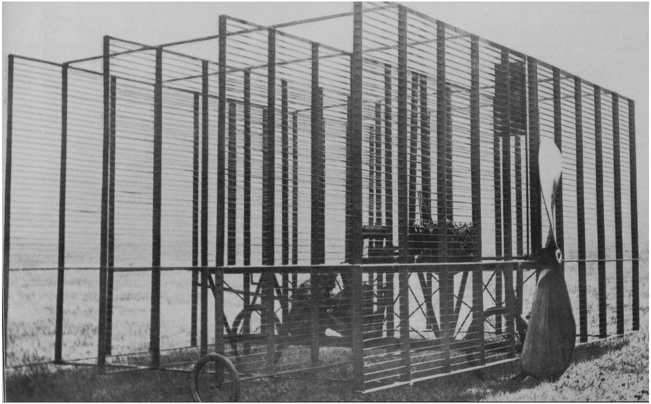
- Horizontal distance between wings (stagger) does not greatly influence interference
- The choice of stagger is mostly determined by visibility and access



- Picture on left shows a Gloster Gladiator with a positive stagger to give upward and aft visibility to the pilot
- Picture on right, the lower wing spar of the Beech Staggerwing provides support for undercarriage.

Multi-planes

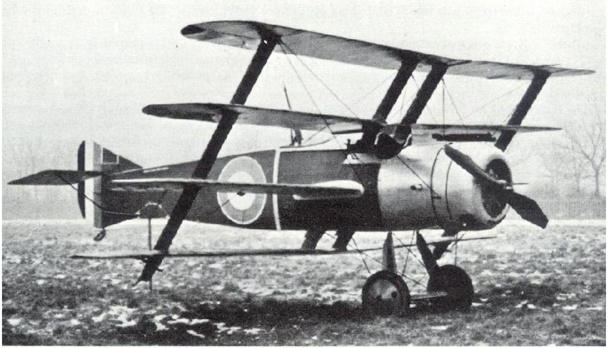
- Trying to extend induced drag savings, bi-plane extended to more than two wings by several designers
- Most extreme example by Horatio Phillips (1907) flew briefly and holds record for highest aspect ratio at 152



- Increased drag from interference not properly understood at time

Reduced Wing Pitching Moment

- Additional advantage of high aspect ratio multi-wing aircraft is reduced pitching moment
- Results in a reduction in down force that tail must provide for trim
- Size of the tail can be reduced as well: example is the 4-winged Armstrong-Whitworth FK 10 shown below



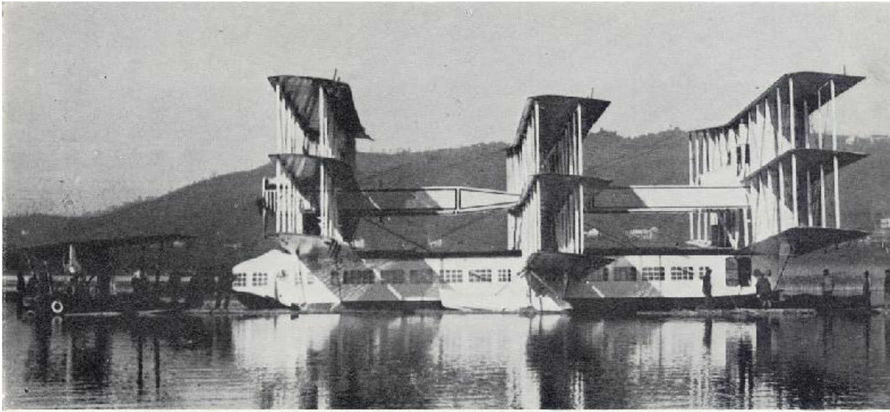
Production-type F.K.10 with 110 h.p. Le Rhône engine.

- These generalizations are true of any high aspect ratio aircraft

Reduced Rolling Inertia

- Pitts-special Aerobatic aircraft still being produced
- Purpose here was reduced rolling inertial enhanced maneuverability and increased bending strength

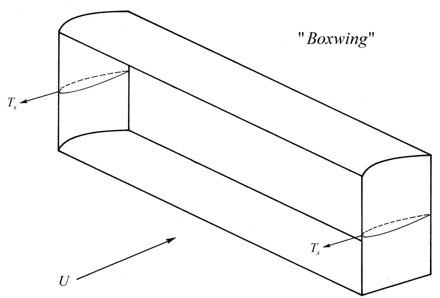
- More wings means more time in construction and more complex structures to attach wings
- Excellent example of having too much of everything is the Caproni Ca-60 which was a fantastic failure

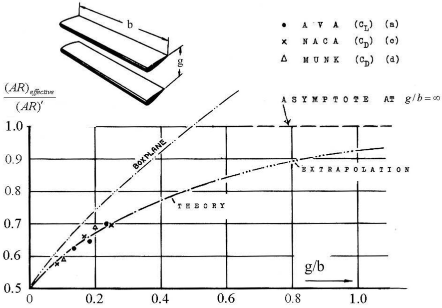


The Caproni Ca 60, here seen at Lake Maggiore, where it achieved its only and unsuccessful flight in 1921.

BoxWing

- Closing off wing tips with an airfoil shaped strut can act as an extremely efficient winglet
- Reduces induced drag even further (than biplane) by reducing strength of wingtip vortices

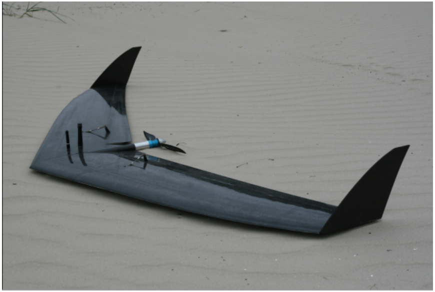




- Above graph shows increase in effective aspect ratio as a function of gap for both the biplane and boxwing

Flying Wing

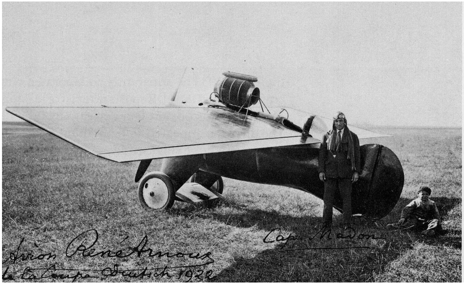
- A flying-wing or tailless aircraft has only one horizontal surface for lift, stability and control
- No tail and minimal fuselage: claim to be a *pure* form of airplane
    - Reduced structural complexity and parasite drag
- Can achieve very high L/D ratios



- To achieve inherent stability, aerodynamic comprises must be made
    - either a reflexed airfoil, or swept and twisted wings
    - Inherently stable flying-wing is often less efficient than a tail-aft design

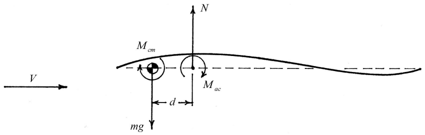
Stability with Reflexed Airfoils

- Most basic form of a tailless aircraft is “Flying Plank” configuration
    - consisting of an unswept wing with no twist and a constant reflexed airfoil



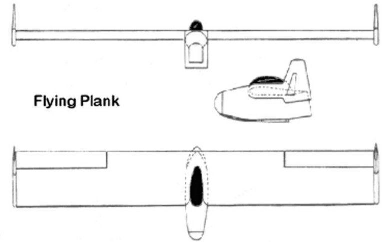

- Pictures show successful 1922 and 1923 Simplex Arnoux racers

- Static stability is achieved when $C_{m_\alpha} < 0$ and trim is achieved when forces/moments balanced
- Flying planks use reflexed airfoil to achieve positive C_{m_0} so trim is possible when CG is in front of NP



- The amount of reflex, and thus trim, is adjusted by moving an elevator-like control surface on the trailing edge of wing
- To fly slower we need higher C_L which means higher α
    - Adjusting control surface so C_m equals zero at higher α
    - achieved by adding nose-up moment $\rightarrow$ trailing edge of control surface up
    - unfortunately this tends to reduce lift by reducing camber

- The classical Flying Plank is the design by Charles Fauvel shown on the left
- However, not all Flying Planks have a rectangular constant-chord wing, as shown by the Marske design on the right

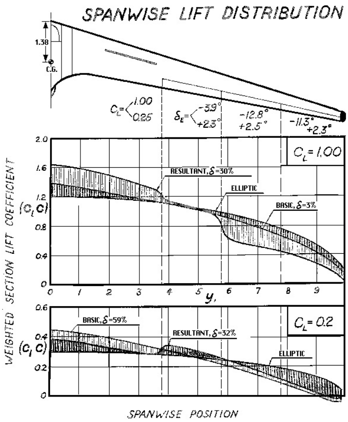


- Main performance limitation of Flying Planks is that reflexed airfoil is inferior to positively-cambered sections
  - minimum-drag condition occurs at a small value of lift coefficient (could be negative)

Stability Through Sweep and Twist

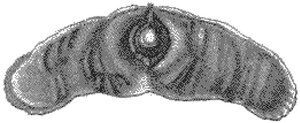
- A more efficient way of achieving stability and trim is by adding sweep and spanwise twist (washout)
- Provide a positive pitching moment with the twist down at tips, thus allowing more efficient airfoils to be used.

- The moment arm from CG to wing tips generally shorter than tail arm on conventional aircraft
  - therefore wing tips must have a lower lift coefficient than typical tail to achieve same degree of stability
  - this increases trim drag, but it can also adversely effect optimal lift distribution of wing
- Good designs find a balance so that these setbacks are not too severe
- In design shown at right, the decreased loading at tip does not severely effect induced drag, but does reduce bending moment at root allowing for lighter structure

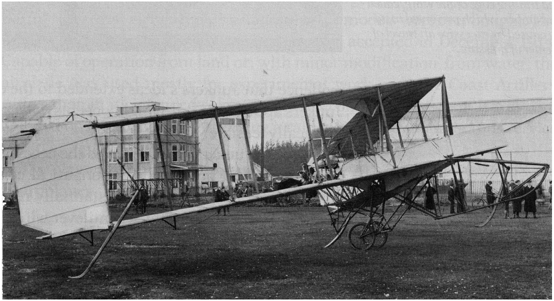


Stability Through Sweep, Twist, and Reflex

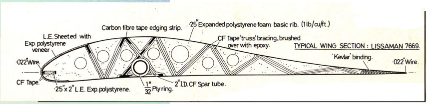
- The idea of using sweep, twist, and reflex for stable flight was inspired by the Zanonia seed
- Dunne D.8 of 1911 was one of earliest successful flying wings to use this methodology; purportedly extraordinarily stable



Makrozanonia Metacarpata (Alsomitra macrocarpa)



- The first successful human-powered aircraft, the Gossamer Condor, was close to flying wing:
  - canard hangs from front boom, operates at near zero lift and helps yaw the aircraft into turns
  - it uses low-pitching moment airfoil and sweep and twist to achieve trim without the canard



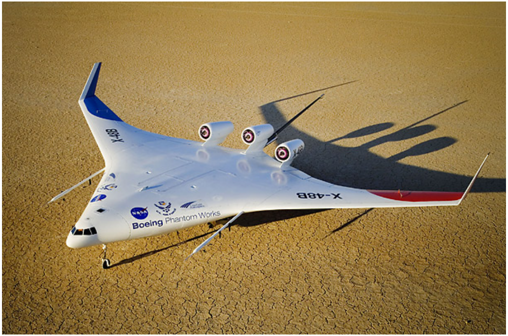
Relaxed Longitudinal Stability

- As with canards, SAS can be used by flying wings to achieve efficiencies exceeding those of tail-aft designs
- Northrop B-2 Bomber shown below is inherently unstable, it lacks reflex and twist (uses aft CG for trim), but SAS provides stability

- UAV Flying Wings can use positive camber airfoils and CG behind NP (unstable but trimmable) with SAS

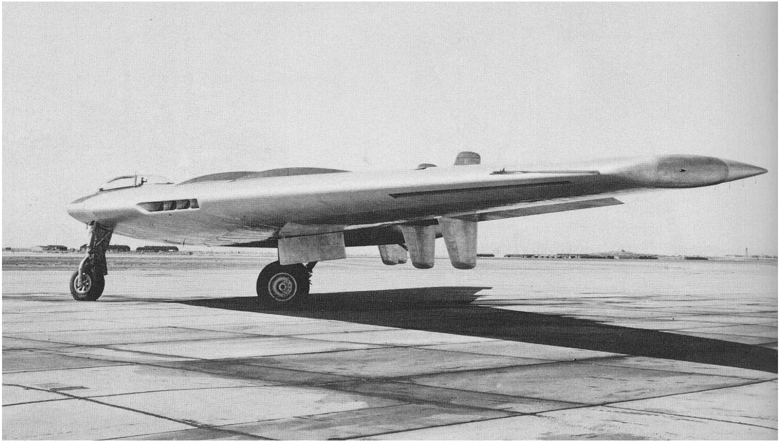
Lateral Stability and Control

- Although Boeing's X-48B is technically a Blended Wing Body (BWB), it is a Flying Wing subtype
- It has large yawing inertia and small distance between *CG* and vertical stabilizers
  - so while sweep helps provide directional and roll stability, dutch roll is still poorly damped
  - can be stabilized (damped) using SAS, still has poor lateral control authority
    - common trait of BWB's and Flying Wings



- Sweep also helps provide directional (weathercock) stability ($C_{n_\beta} > 0$) by presenting larger span to wind in a sideslip
- Sweep also provides static roll-stability ($C_{l_\beta} < 0$)
- Propellers act as vertical fins giving a net side force/yaw moment in sideslip

- B-35 was converted to jet power in 1947 (becoming B-49)
  - four vertical tails added to compensate for loss in directional stability



- Thick airfoil provides large volume for payload, crew and engines
- Thick airfoil limited speed to 640 kph due to drag divergence
- Program cancelled in 1949

Spanloading

- Though concept not limited to flying-wings, *spanloading* provides structural relief by distributing load more evenly over lifting surface
- AeroVironment's solar-powered Helios possibly best example of this concept.

- Enormous yawing and rolling inertia and comparatively small pitch inertia would make this aircraft difficult to handle without SAS

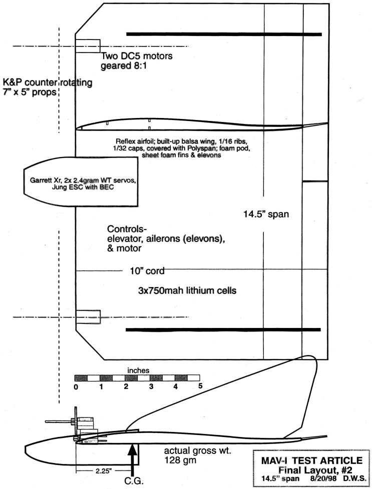
Low Aspect Ratio Flying Wings

- V-173 *flying flapjack* (1942), by NACA engineer Charles Zimmerman was an extraordinarily low AR flying wing
- Low aerodynamic efficiency of low AR overcome by propellers rotating in direction to cancel tip vortices
- Stall angle of low AR FW is very high, combined with high-thrust rotors gives short take-off and landing (STOL)

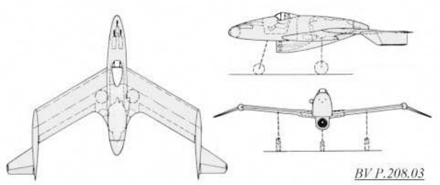
- Another notable low AR design is the Arup by Dr. Snyder (1930)
- Dr. Snyder was a podiatrist, and was inspired by a heel-shaped shoe insert.

- Design was later refined by a professional aeronautical engineer and while not aerodynamically efficient was compact and strong

- The STOL ability of such designs is being revisited for Micro Air Vehicle (MAV) applications
- Results show promise for high performance within compact size limitations imposed on MAV's.



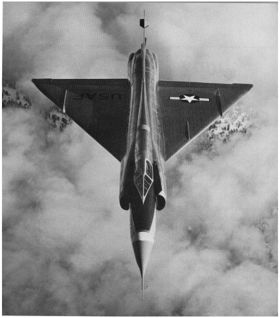
- The configuration developed by Blohm and Voss in World War II has been recently revisted
- Glider tests at Naval Research Laboratory and wind-tunnel tests University of Toronto have shown good efficiency for its relatively short span



- The aft stabilizing surfaces act both like a horizontal tail and winglets
  - benefiting from upwash spilling off the wing tip
  - tilts lift vector forwards and producing a reduction in drag
  - main wing can use efficient airfoil with no twist

Delta Wing

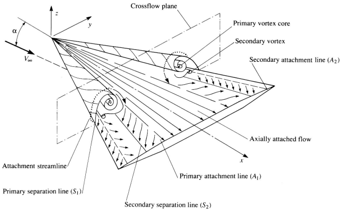
- Delta wing configuration typically seen on supersonic aircraft,
- Reduces wave drag and attains high lift coefficient required for landing at reasonable speeds
- Small span also reduces the bending moment at the root allowing large g-loadings with minimal structure

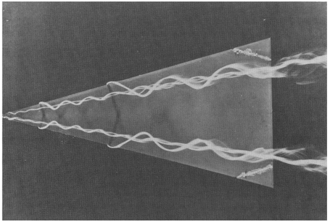


- F-102 Delta Dagger (1955), shown above, one of first delta wings
- Lift coefficients very low at high speeds → induced drag is low compared to friction, form and wave drag

Bound Leading-Edge Vortex

- The sharp-edged highly-swept wing generates stable bound vortex at the leading edge when at angle of attack
- This vortex energizes flow on the upper surface of wing, creates pocket of low pressure air $\rightarrow$ high lift coefficients attained at high angles of attack

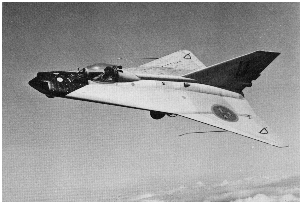




- Comes at price of high drag coefficients
- Allow delta-winged aircraft with high thrust to take-off and land at reasonable speeds
- High drag beneficial on landing

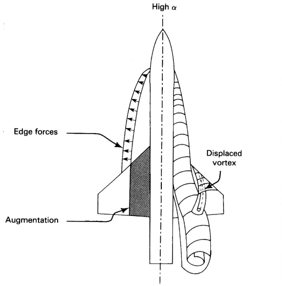
Compound Delta Wing

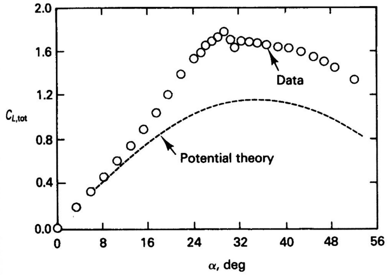
- Compound delta wing offers improved efficiency at higher lift coefficients.
- Used on most second generation delta wing aircraft, such as Saab Draken (1950s), NASA Shuttle, and Concord



- Compound blend allowed Concord to take off and land from existing runways

- The bound vortex effect used to enhance the low-speed behaviour of compound delta wings
- The inner highly-swept portion generates the bound vortex
- Outer wing higher AR improves overall efficiency





- Small wing area that is optimal for cruise requires large lift coefficient

Summary

- Choice of configuration depends on payload, objectives and constraints
- Generally, performance is limited by stability requirements
- With modern SAS, or full-authority feedback control previously uncontrollable, but efficient configurations are possible
- Canards provide maneuverability, and improved stall at the price of increased trim drag
- Tandem wings provide decreased induced drag and rolling inertia, but with interference effects
- Biplanes have the similar trade-offs to Tandem wings, but with improved structural properties
- Flying wings offer a minimalist design, but with a loss in wing efficiency and potential handling qualities issues
- Delta wings offer high lift coefficients for transonic and supersonic wings