Lecture # 31: 3D Wing Aerodynamics:

- Introduction

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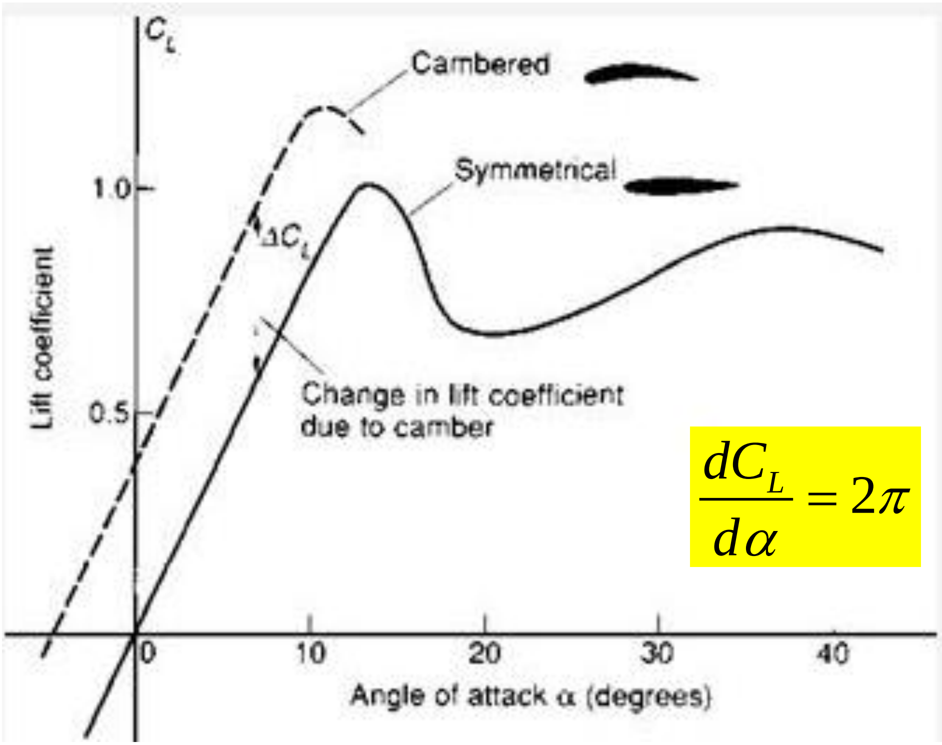
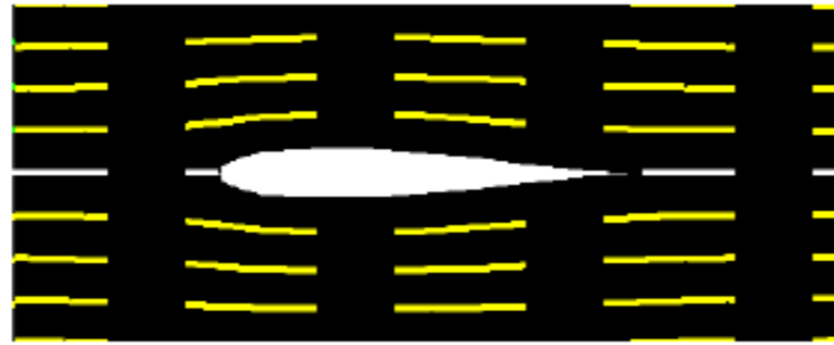
❑ Thin Airfoil Theory – for 2D Airfoil



$$\frac{dC_L}{d\alpha} = 2\pi$$



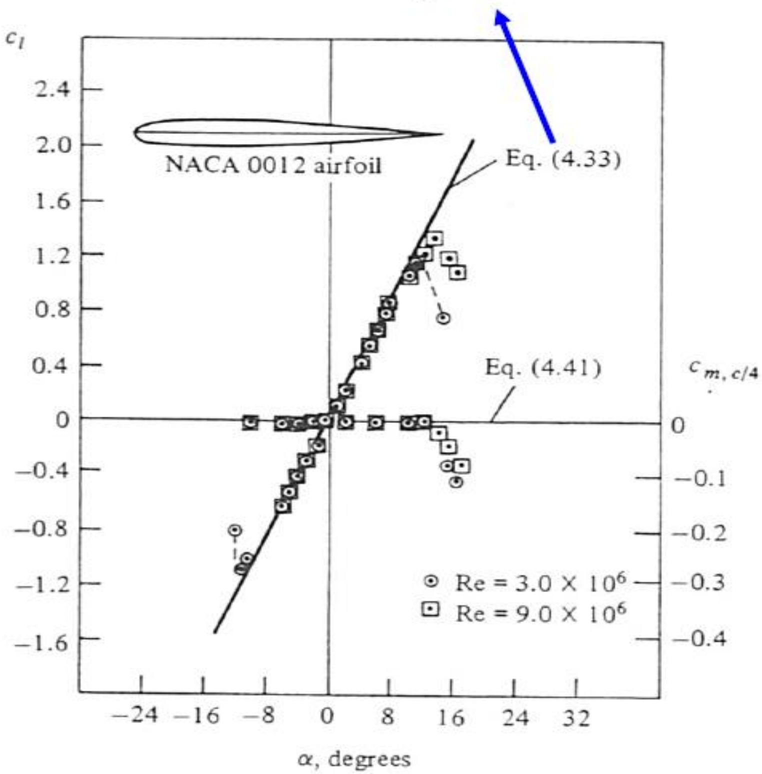
- ***Thin airfoil theory was developed for predictions of aerodynamic performance of 2D airfoils with infinite wingspan.***

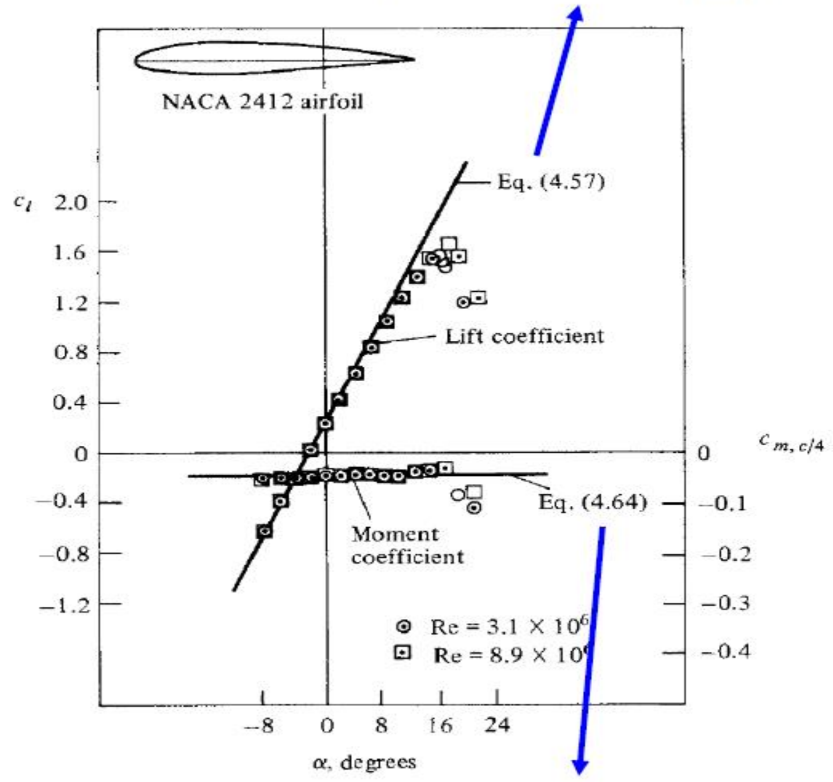
Thin Airfoil Theory – 2D Airfoil

- ***Center of Lift or center of pressure on an airfoil***

$$c_l = 2\pi\alpha$$

$$c_l = 2\pi(\alpha - \alpha_{L=0})$$





$$C_{M,c/4} = 0$$

$$C_{M,c/4} = -\frac{\pi}{4}(A_1 - A_2)$$

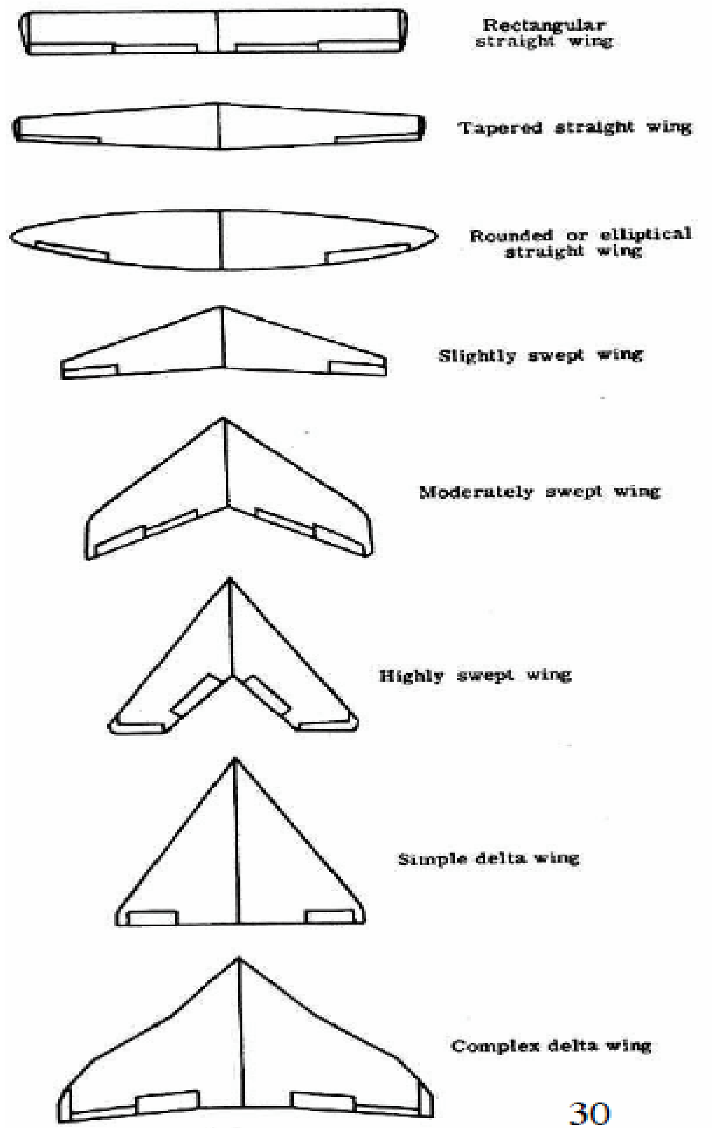
- ***The predictions of the thin airfoil theory may not valid for the 3D airfoils with limited wingspan.***

❑ 3D Wing Aerodynamics

• *While 2D airfoils has infinite wingspan, all real wings are finite in span – 3D wings.*

Wing Design Parameters

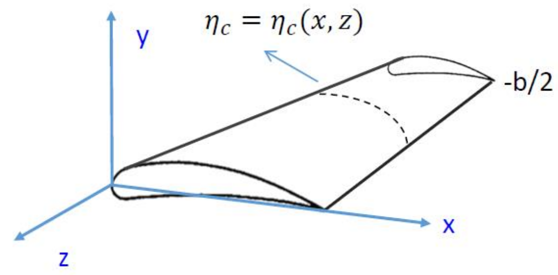
- Planform
  - Aspect ratio
  - Sweep
  - Taper
  - Complex geometries
  - Shapes at root and tip
- Chord section
  - Airfoils
  - Twist
- Movable surfaces
  - Leading- and trailing-edge devices
  - Ailerons
  - Spoilers
- Interfaces
  - Fuselage
  - Powerplants
  - Dihedral angle

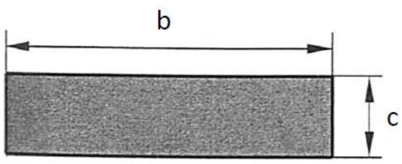


3D Wing Aerodynamics

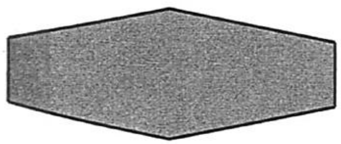
- Wingspan = b, wing area=S
- Aspect ratio

$$AR = b^2/S$$

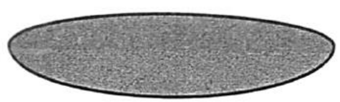




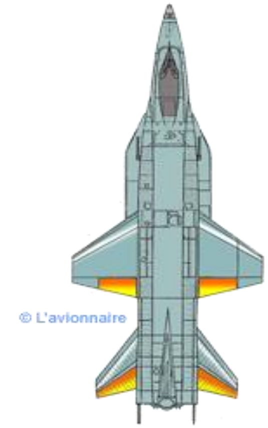
rectangular wing



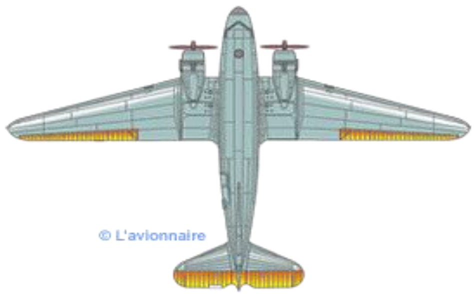
trapezoidal wing



elliptical wing



Low aspect ratio
(North American X15)



Moderate aspect ratio
(Douglas DC 3)

High aspect ratio
(Breguet 904 Nymphale)

Aspect Ratio

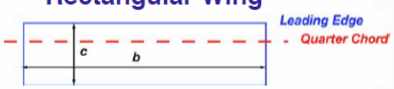
$$AR = \frac{b}{c} \quad \text{rectangular wing}$$

$$= \frac{b \times b}{c \times b} = \frac{b^2}{S} \quad \text{any wing}$$

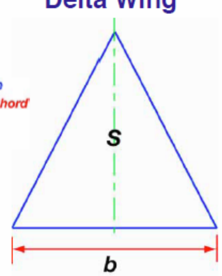
Taper Ratio

$$\lambda = \frac{c_{tip}}{c_{root}} = \frac{\text{tip chord}}{\text{root chord}}$$

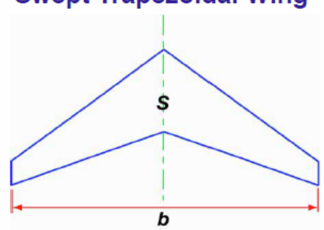
Rectangular Wing



Delta Wing



Swept Trapezoidal Wing



❑ 3D Wing Aerodynamics

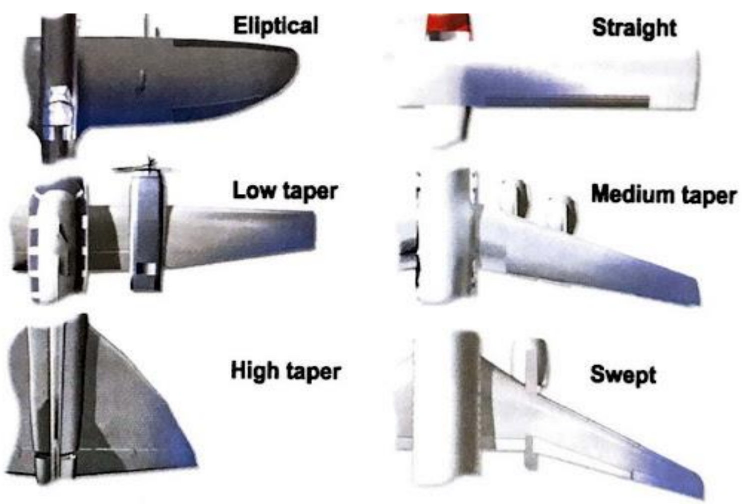
- ***Constant chord :*** *parallel leading & trailing edges. Simplest to make, and common where low cost is important.*
- ***Constant chord with Tapered Outer : T****his is midway between the rectangular and the tapered wing. Common variant seen for example on many Cessna types.*
- ***Tapered :*** *wing narrows towards the tip. Structurally and aerodynamically more efficient than a constant chord wing, and easier to make than the elliptical type.*
- ***Trapezoidal :*** *a tapered wing with straight leading and trailing edges: may be unswept or swept. The straight tapered wing is one of the most common wing planforms.*
- ***Elliptical :*** *aerodynamically, the elliptical planform is the most efficient as elliptical spanwise lift distribution has the lowest possible induced drag. The most important disadvantage is that its manufacturability is poor.*

Constant chord
(Broussard)

Constant chord with tapered
outer (Cessna)

Tapered trapezoidal
(Mustang P51)

Elliptical
(Spitfire)

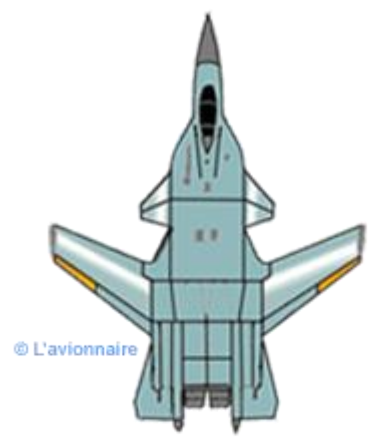


❑ 3D Wing Aerodynamics

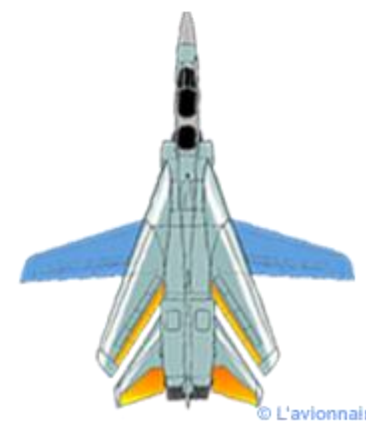
- **[Wing sweep:]** *Wings may be swept back, or occasionally forwards, for a variety of reasons. A small degree of sweep is sometimes used to adjust the center of lift when the wing cannot be attached in the ideal position for some reason, such as a pilot's visibility from the cockpit. Other uses are described below.*
- ***Straight :** extends at right angles to the line of flight..*
- ***Swept back (aka "swept wing") :** The wing sweeps rearwards from the root to the tip.*
- ***Forward swept :** the wing angles forward from the root.*

Straight
(Curtiss P40)

Conventional tail
(Mystere IV)



Forward swept
(Sukhoî SU-47)



Variable sweep
(Dassault 3G)

❑ 3D Wing Aerodynamics

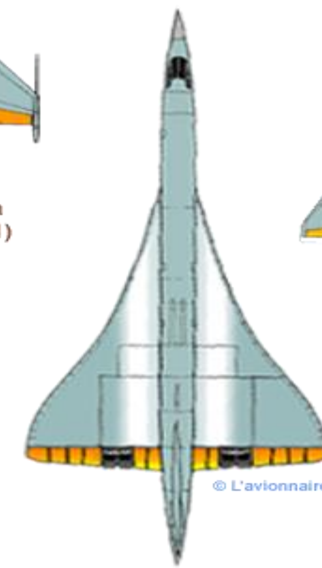
- **Wing Delta:** *Delta triangular planform with swept leading edge and straight trailing edge.*
  - *Offers the advantages of a swept wing, with good structural efficiency and low frontal area.*
  - *Disadvantages are the low wing loading and high wetted area needed for aerodynamic stability.*
- ***Tailless delta :*** *a classic high-speed design.*
- ***Tailed delta:*** *with a tailplane to improve handling.*
- ***Cropped delta :*** *wing tips are cut off to avoid tip drag at high angles of attack.*
- ***Compound delta or double delta :*** *inner section has a (usually) steeper leading-edge sweep to improve the lift at high angles of attack and delays or prevents stalling.*
- ***Ogival delta:*** *a double-curve encompassing the leading edges and tip of a cropped compound delta.*

Tailess delta
(Mirafe III)

Tailed delta
(Mig-21)

Cropped delta
(Fiarley Delta 1)

Compound delta
(Saab 35 Draken)



Ogival delta (Concordde)

❑ 3D Wing Aerodynamics

- ***Trapezoidal wing :*** *This high-performance wing is characterized by low elongation with a positive-boom leading edge while the trailing edge has a negative boom.*

- ***Flying wing :*** *the aircraft has no distinct fuselage or horizontal tail (although fins and pods, blisters, etc. may be present*

Trapezoidal wing
(Lockheed F-22)

Flying wing
(Northop B2)

- ***Stealth - How Does it Work? (Northrop B-2 Spirit)***

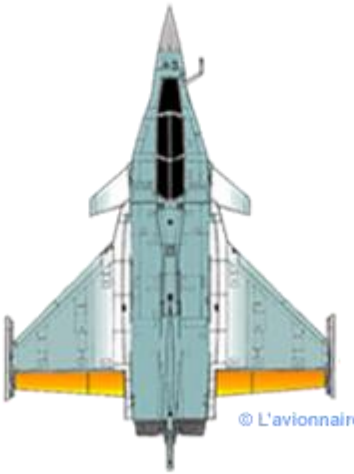
https://www.youtube.com/watch?v=ya8umwgtsLw

❑ 3D Wing Aerodynamics

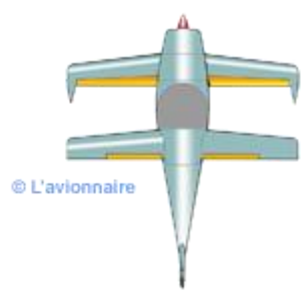
- ***Tailplanes and foreplanes:*** *The classic airfoil section wing is unstable in pitch, and requires some form of horizontal stabilizing surface. Also it cannot provide any significant pitch control, requiring a separate control surface (elevator) mounted elsewhere.*

- ***Conventional :*** *"tailplane" surface at the rear of the aircraft, forming part of the tail or empennage.*
- ***Canard :*** *"foreplane" surface at the front of the aircraft. Common in the pioneer years, but from the outbreak of World War I no production model appeared before 1967.*
- ***Tandem :*** *two main wings, one behind the other. Both provide lift; the rear wing provides pitch stability (like a normal tailplane). To ensure longitudinal stability, the wings must have different aerodynamic characteristics: in general, the wing loading and/or the airfoils differ between the two wings.*
- ***Three surface :*** *both conventional tail and canard auxiliary surfaces.*

Conventional tail
(Mystere IV)



Canard
(Rafale)



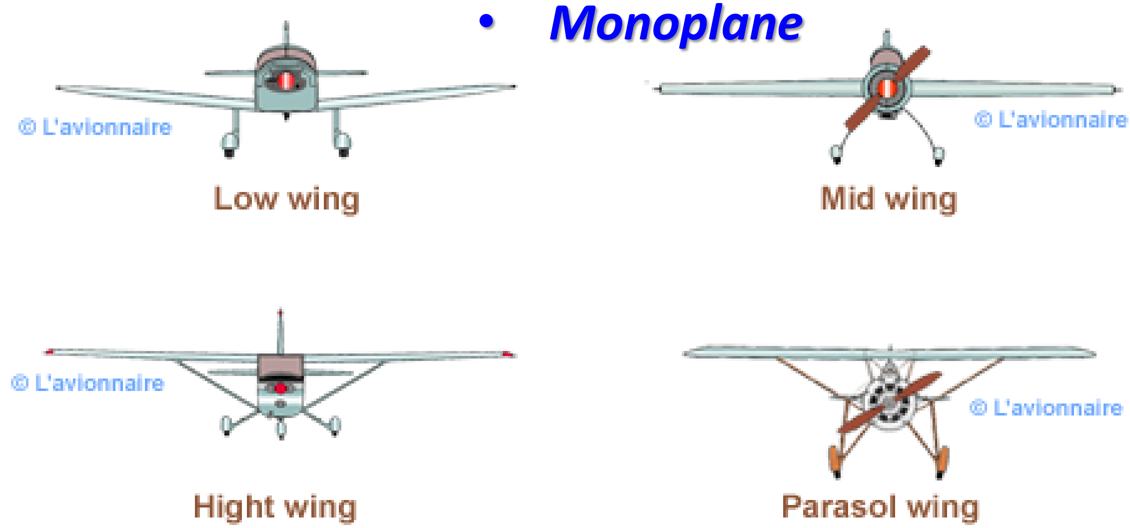
Tandem
(Rutan Quickie)

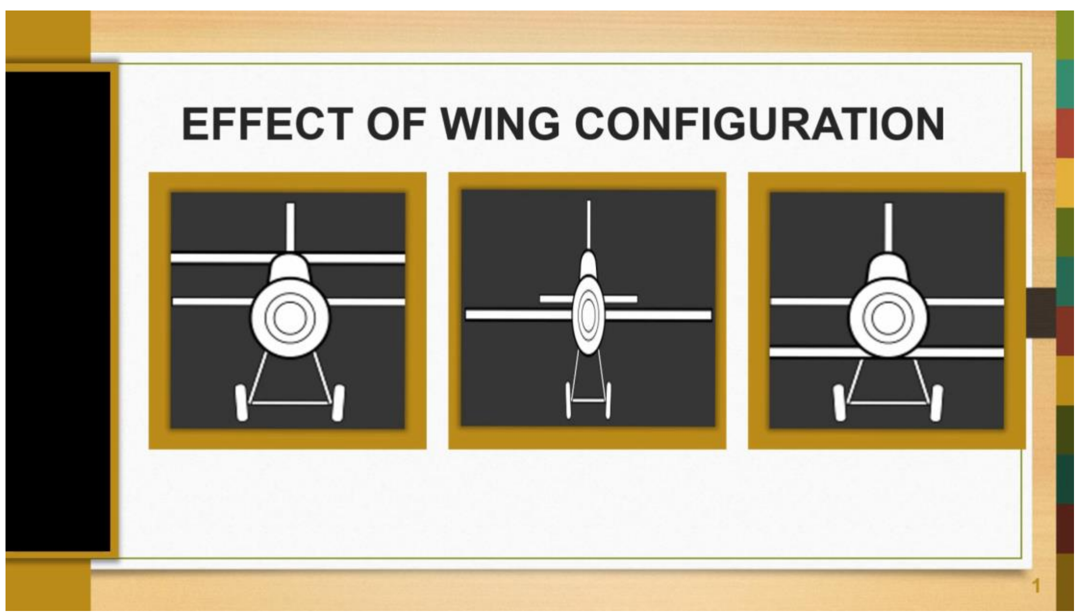
Three surface
(Sukhoi 34)

❑ 3D Wing Aerodynamics

- ***Low wing :*** *mounted near or below the bottom of the fuselage.*
- ***Mid wing :*** *mounted approximately halfway up the fuselage.*
- ***High wing :*** *mounted on the upper fuselage.*
- ***Parasol wing :*** *raised clear above the top of the fuselage.*

- ***Monoplane***

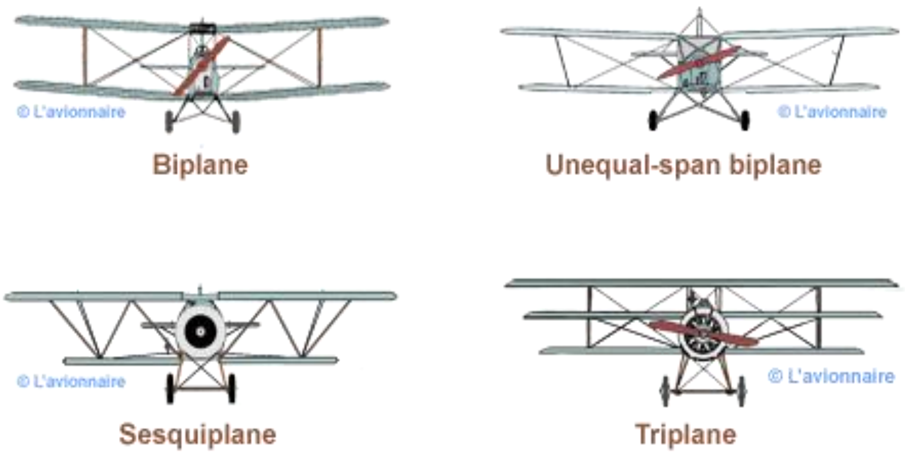




❑ 3D Wing Aerodynamics

- ***Biplane*** *is inherently lighter and stronger than a monoplane and was the most common configuration until the 1930s.*
- ***Unequal-span biplane :*** *a biplane in which one wing (usually the lower) is shorter than the other.*
- ***Sesquiplane :*** *literally "one-and-a-half planes" is a type of biplane in which the lower wing is significantly smaller than the upper wing, either in span or chord or both.*
- ***Triplane:*** *3 planes stacked one above another.*

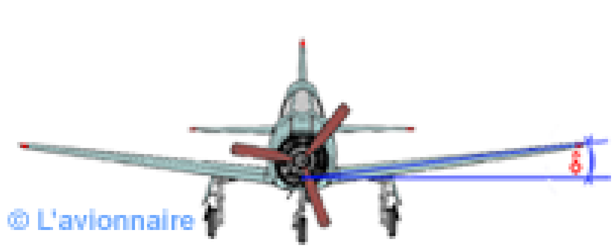
- ***Multi-plane***



Wright Brothers' Biplane Design

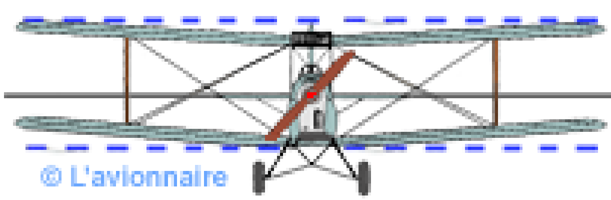
❑ 3D Wing Aerodynamics

- ***Dihedral and anhedral:*** *Angling the wings up or down spanwise from root to tip can help to resolve various design issues, such as stability and control in flight.*
- ***Dihedral:*** *the tips are higher than the root as giving a shallow 'V' shape when seen from the front. Adds lateral stability.*
- ***Anhedral:*** *the tips are lower than the root, the opposite of dihedral. Used to reduce stability where some other feature results in too much stability.*
- *Some biplanes have different degrees of dihedral/anhedral on different wings.*

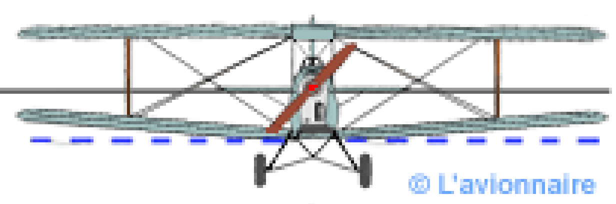


Dihedral

Anhedral



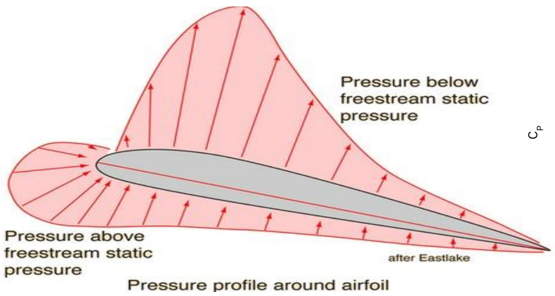
Biplan with dihedral on both wings

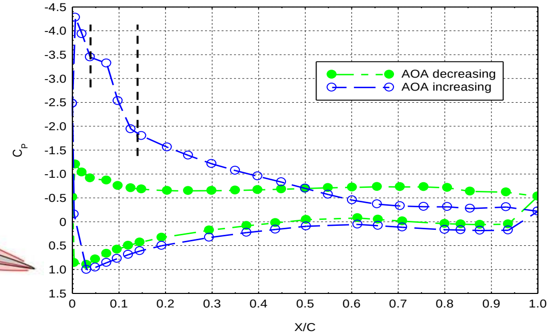


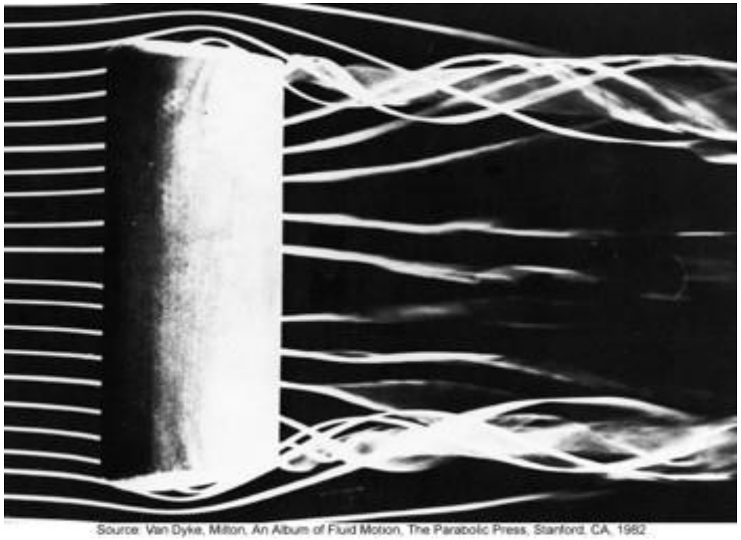
Biplan with dihedral on lever wing

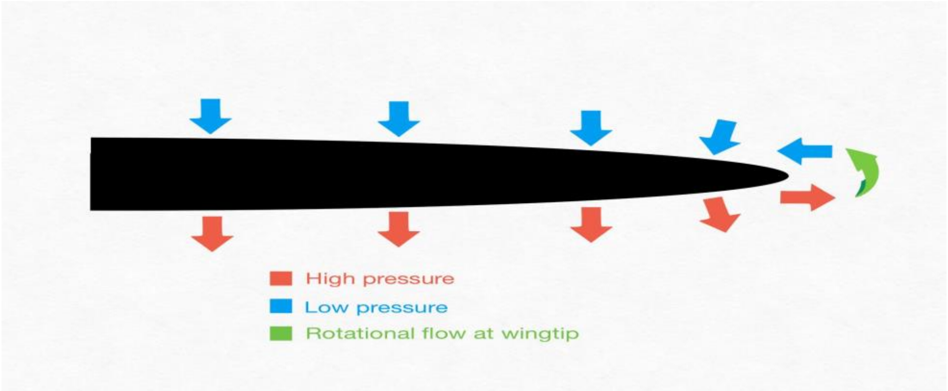
❑ 3D Wing Aerodynamics

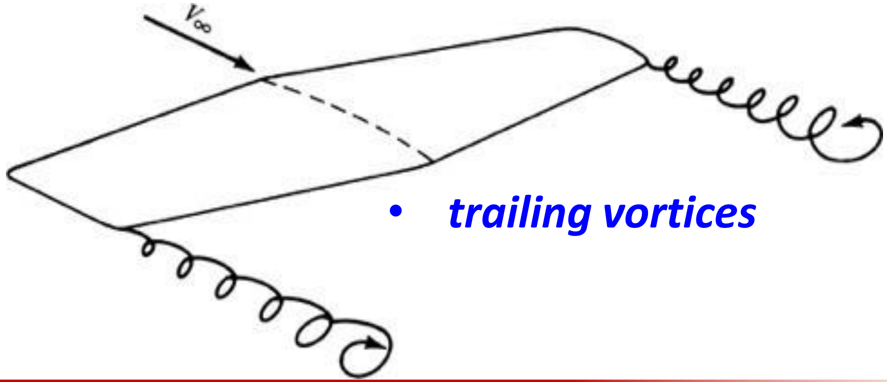
- ***Air flow leaks around wing tips produces a trailing vortex at each wing tip.***



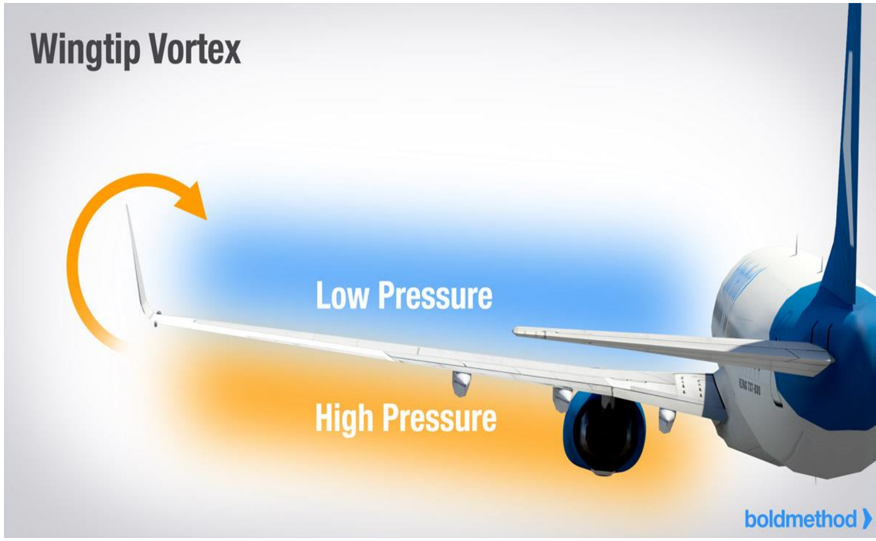






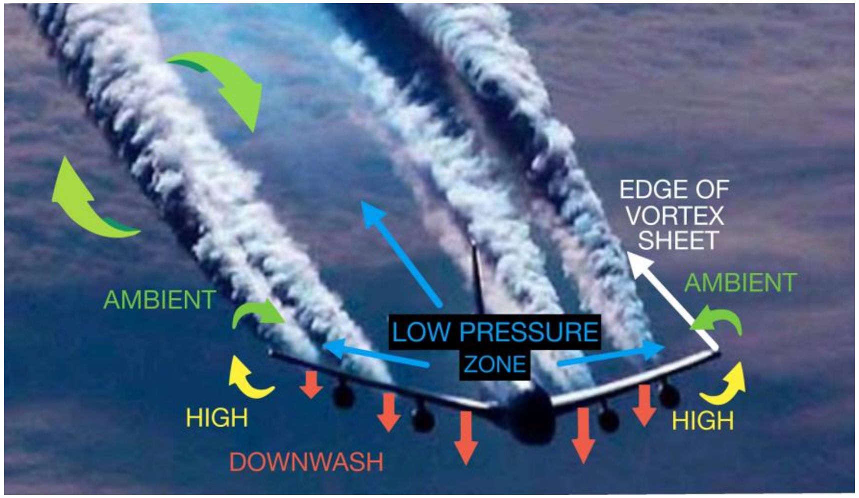


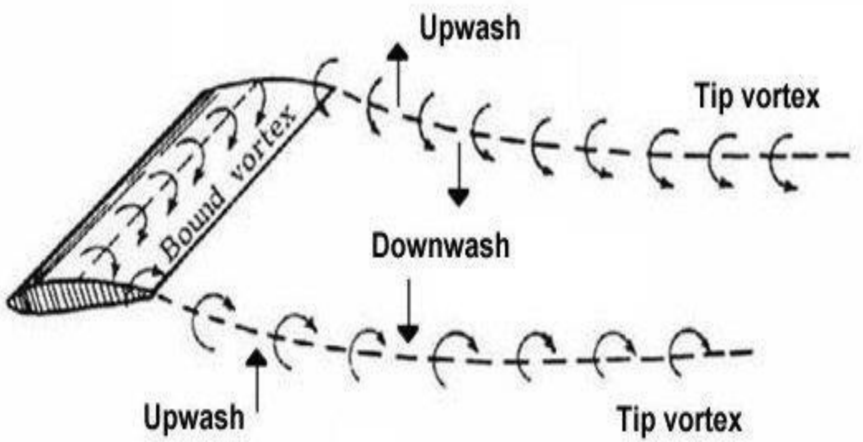
- ***trailing vortices***

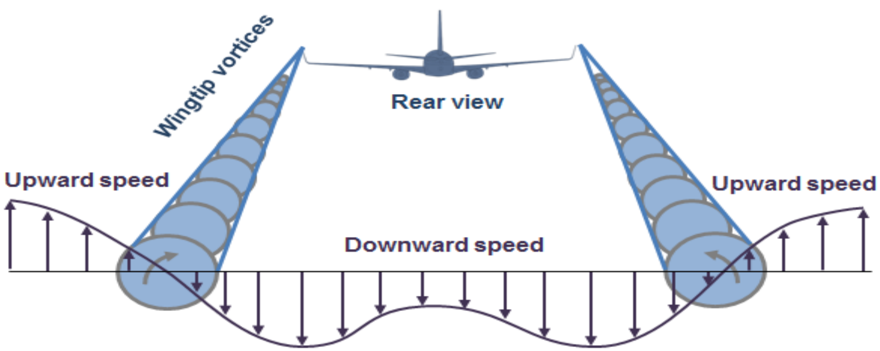


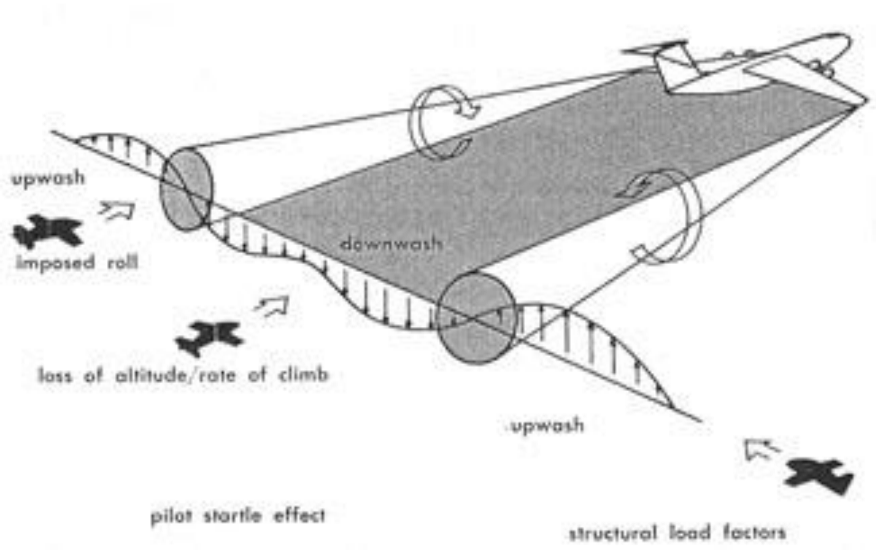
❑ 3D Wing Aerodynamics

- *Trailing vortices at each wing tip would drag the surrounding air inducing a velocity component in the downward direction - downwash.*
- *The downwash combines with the local freestream to create a local relative wind.*



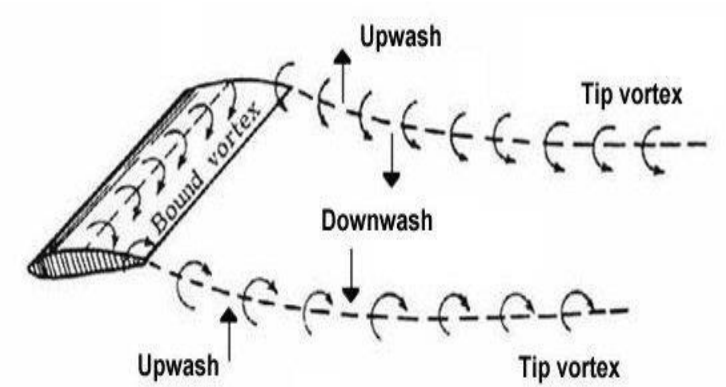






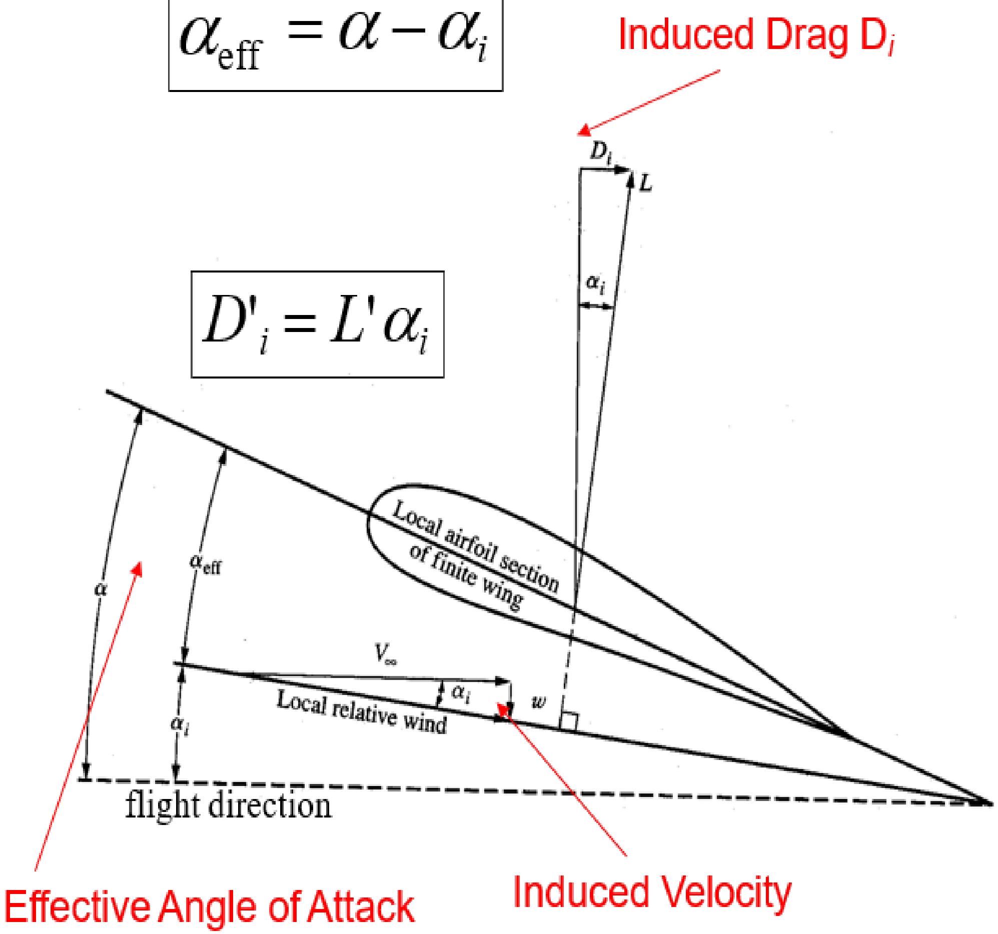
❑ 3D Wing Aerodynamics

- ***Downwash and Induced Drag***



$$\alpha_{\text{eff}} = \alpha - \alpha_i$$

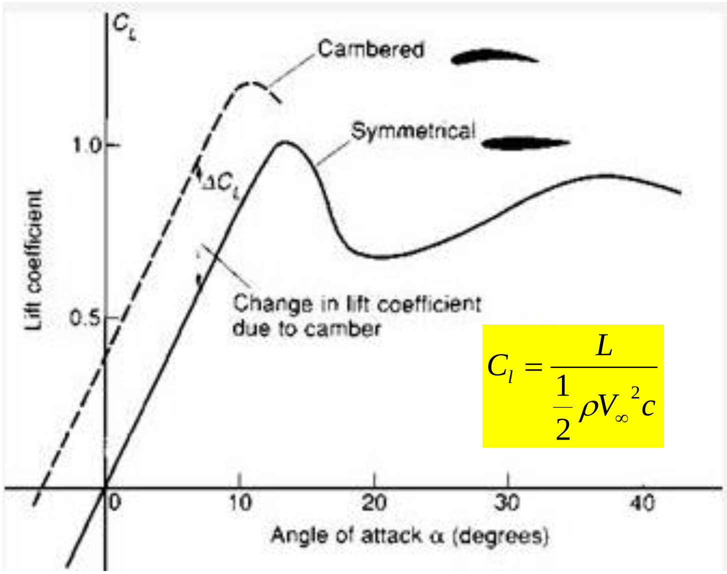
$$D'_i = L'\alpha_i$$



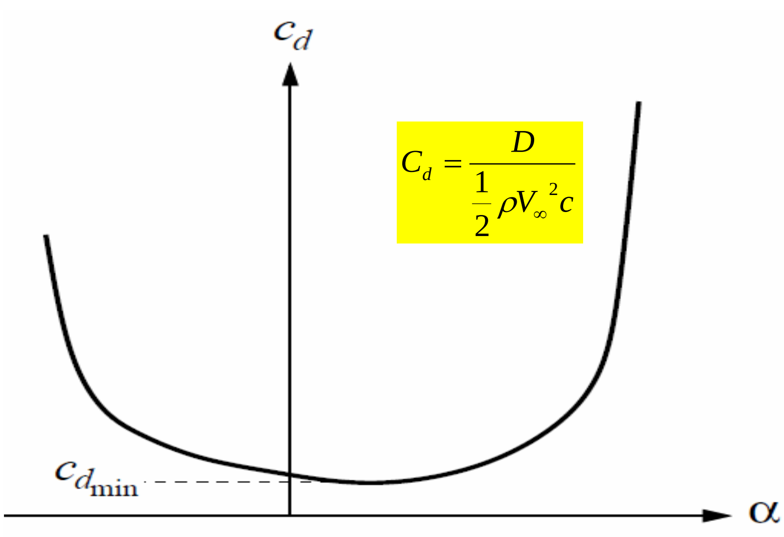
The downwash has two important effects:

- ***The effective angle of attack is reduced to cause lift reduction.***
- ***Induced drag is created due to tilting of the local lift vector.***

❑ 3D Wing Aerodynamics



$$C_l = \frac{L}{\frac{1}{2}\rho V_\infty^2 c}$$



$$C_d = \frac{D}{\frac{1}{2}\rho V_\infty^2 c}$$

The downwash has two important effects:

- *The effective angle of attack is reduced to cause* ***lift reduction****.*
- ***Induced drag*** *is created due to tilting of the local lift vector.*

- https://www.youtube.com/watch?v=e3yD3QEh96o&t=189s

- https://www.youtube.com/watch?v=stNKrsiw6UA&t=84s