Wing Design: Major Decisions

- Wing Area / Wing Loading
- Span / Aspect Ratio
- Planform Shape
- Airfoils
- Flaps and Other High Lift Devices
- Twist

Wing Design Parameters

- First Level
  - Span
  - Area
  - Thickness
- Detail Design
  - Planform shape
    - Taper
    - Sweep
    - Tips
  - Airfoils
  - Twist

Factors affecting wing size

- Cruise Drag
- Stall Speed
- Take off and landing distance
- Maneuver
  - Instantaneous
  - Sustained
- Fuel Volume
- Hangar size

Span Considerations

- **Climb**
  - Induced drag important at climb airspeeds
  - Greater span good for rate of climb
- **Cruise**
  - High altitude: induced drag significant, greater span preferred
  - Low Altitude: parasite drag dominates, span less important
- **Weight**
  - Increasing span and aspect ratio makes the wing heavier.
  - Optimum is a compromise between wing weight and induced drag
- **Ground Handling**
  - Taxiways and runway lights
  - Hangar size

Wing Area

- **Cruise Drag**
  - Low altitude cruise favors high wing loading and low wetted area.
  - Higher altitude cruise favors lower wing loading and greater span.
- **Takeoff and Landing**
  - Increasing wing loading increases takeoff and landing roll
  - Roll is proportional to the square of the takeoff or landing speed
- **Maneuvering**
  - Favors low wing loading, particularly for instantaneous turn rate.
- **Stall Speed**
  - Most light airplanes wings are sized by stall speed requirements
  - FAR part 23, Part 103
  - Survivability

Cruise Optimum Wing

For a given altitude and airspeed:

$$D = D_{body} + D_{misc.} + C_{d0w} Sq + \frac{C_L^2}{\pi e A} Sq$$

Differentiating wrt. wing area and setting derivative to zero gives:

$$C_{d0w} = \frac{C_L^2}{\pi e A}$$

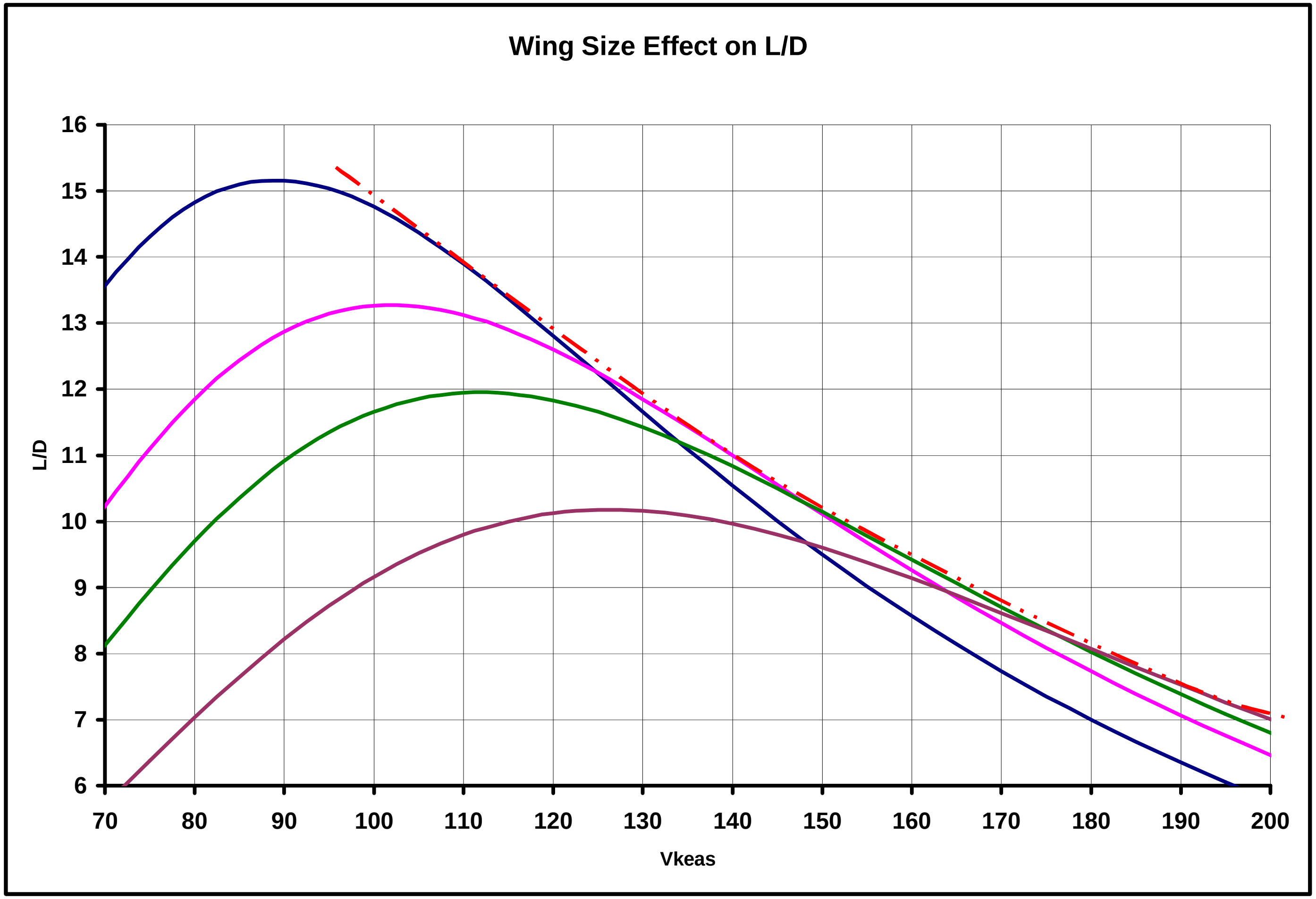
This is the condition for best wing L/D

Accordingly: for optimum cruise: size wing to fly at best wing L/D

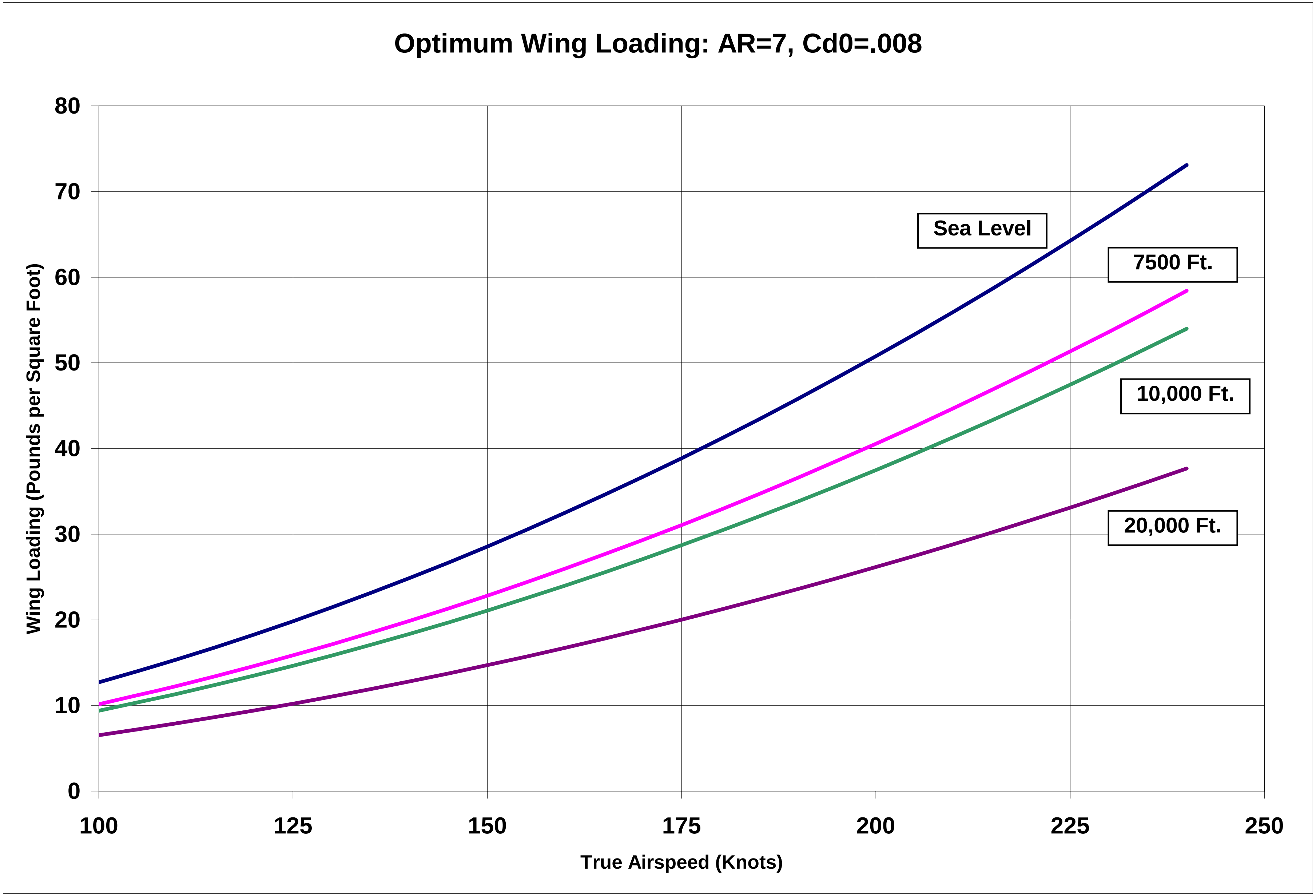
$$C_{Lopt} = \sqrt{C_{d0w} \pi e A}$$

$$\boxed{S = W/(q\sqrt{C_{d0w} \pi e A})}$$

Cruise Optimized Wing

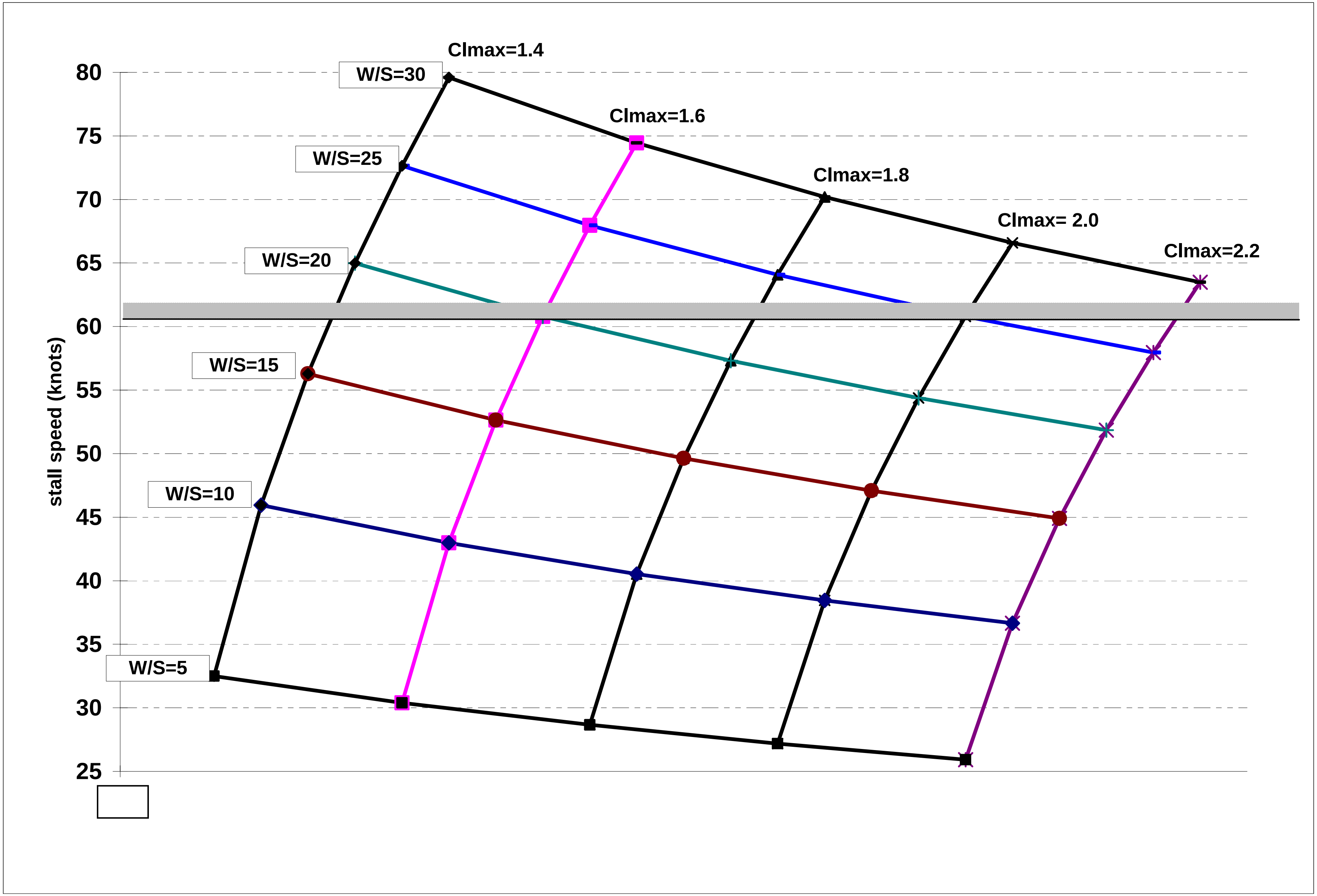


Airplane with wing optimized for given equivalent airspeed does not fly at best airplane L/D

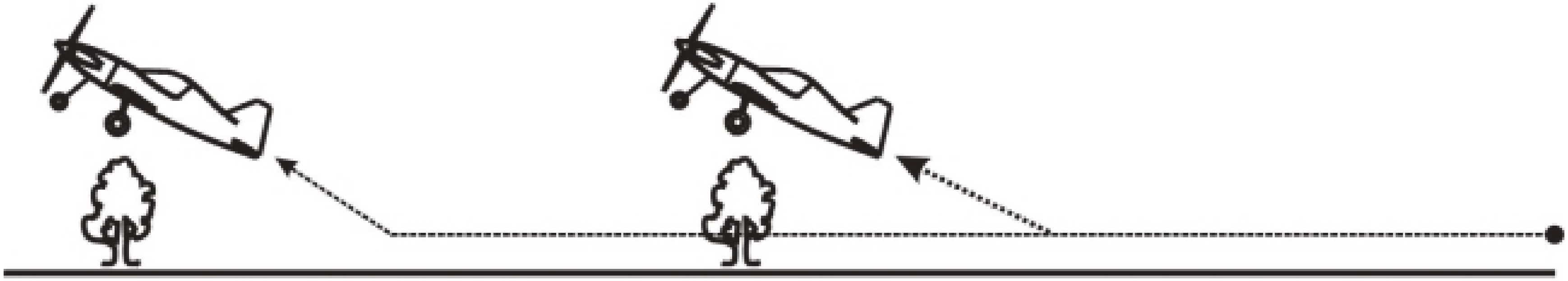


Optimum Wing Loading: AR=7, Cd0=.008

Stall Speed Sized Wing

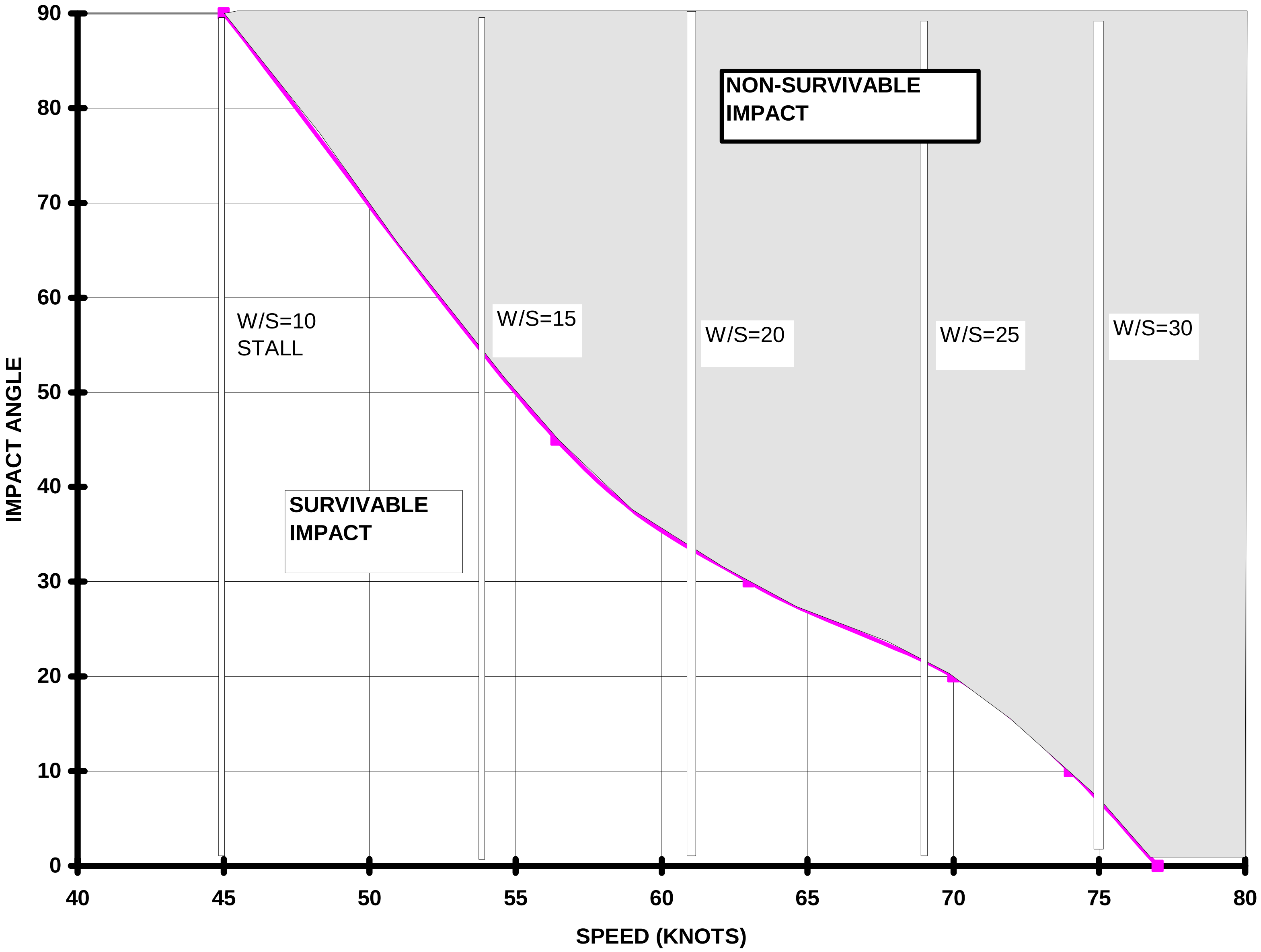


Stall Speed Drives Takeoff Distance

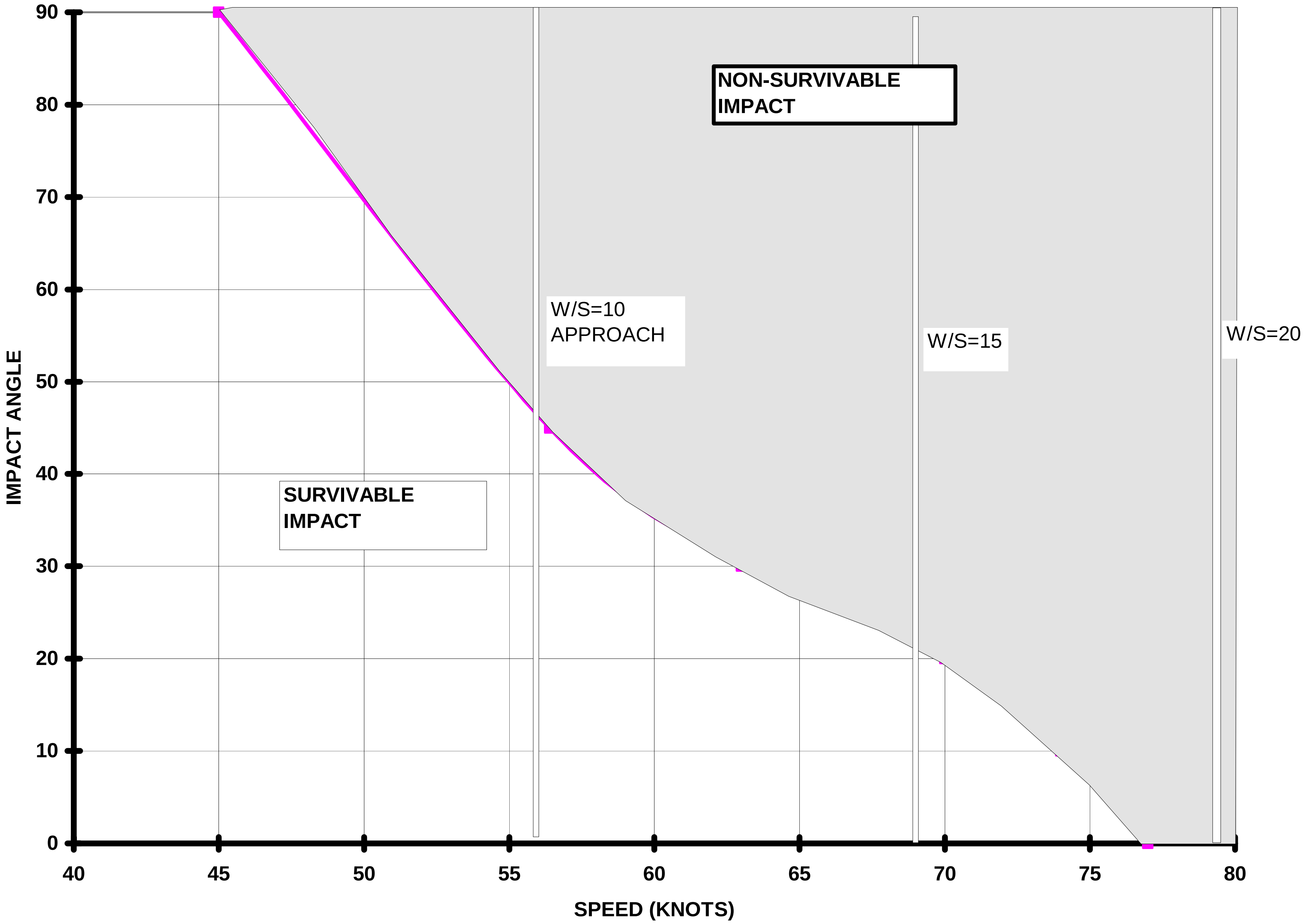


The length of the takeoff roll is proportional to the lift off speed squared. A relatively small reduction in lift off speed can significantly reduce ground roll.

CRASH SURVIVABILITY



CRASH SURVIVABILITY

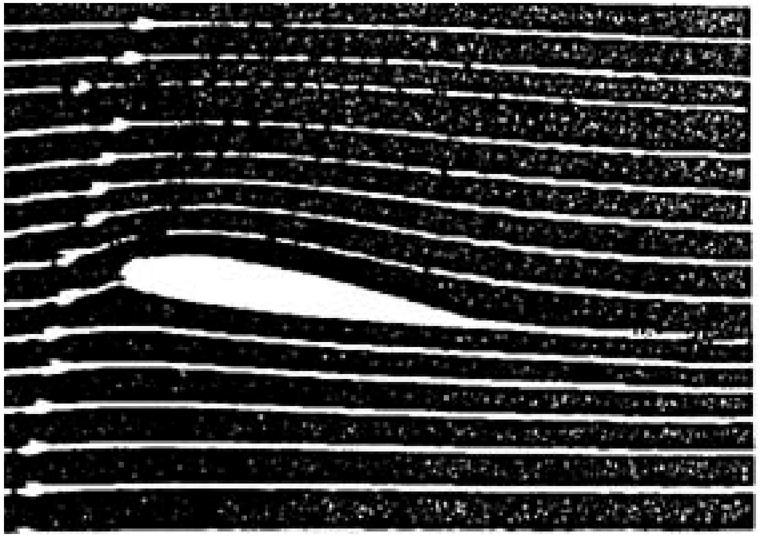


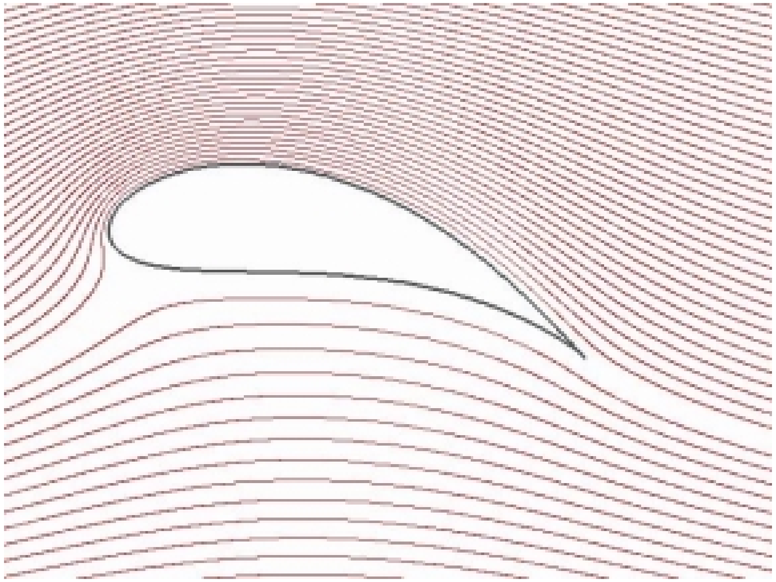
Wing Thickness

- **Wing weight is strongly affected by thickness, particularly for cantilever wings.**
  - Thicker is lighter
- **Supersonic wave drag is a strong function of t/c**
- **Variation of parasite drag with wing t/c is small at subsonic, subcritical speeds.**
  - Drag is primarily skin friction
  - Large drag increase if wing gets so thick that flow separates
- **Thickness taper**
  - Wing weight most strongly affected by root depth
  - Tapering t/c from root to tip can provide lighter wing for given parasite drag.

Airfoils

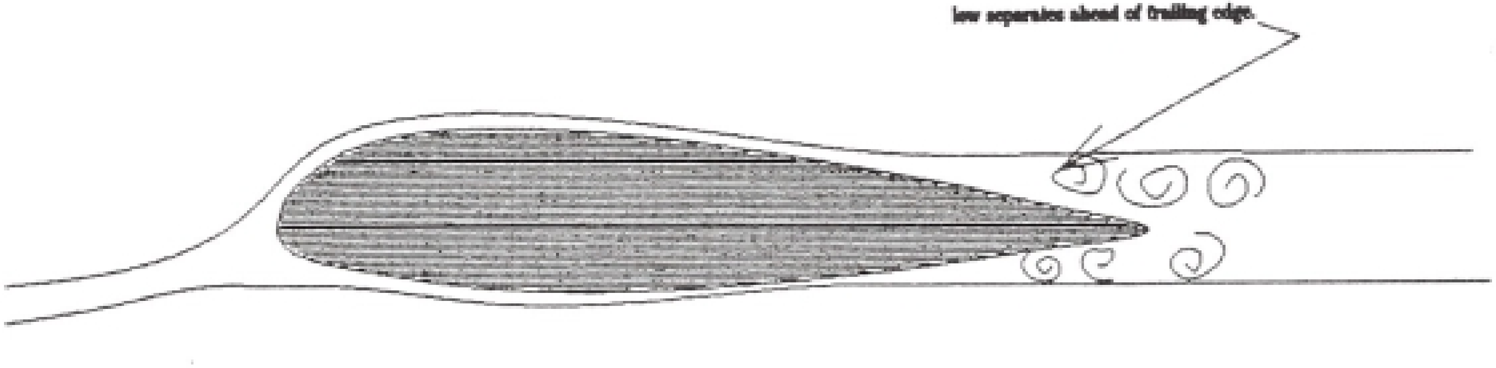
Airfoil Airflow



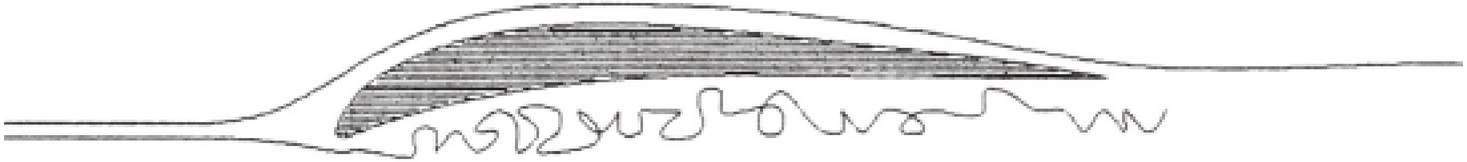


- Airfoil Generates Lift By Deflecting Streamlines Downward
- Momentum Change in Deflected Air Causes Pressure Changes That Act on Wing
- Air Flowing Over Upper Surface at Leading Edge Does Not Meet “Neighbor” Air at Trailing Edge

Flow Very Thick Airfoil



Flow Over Very Thin Airfoils

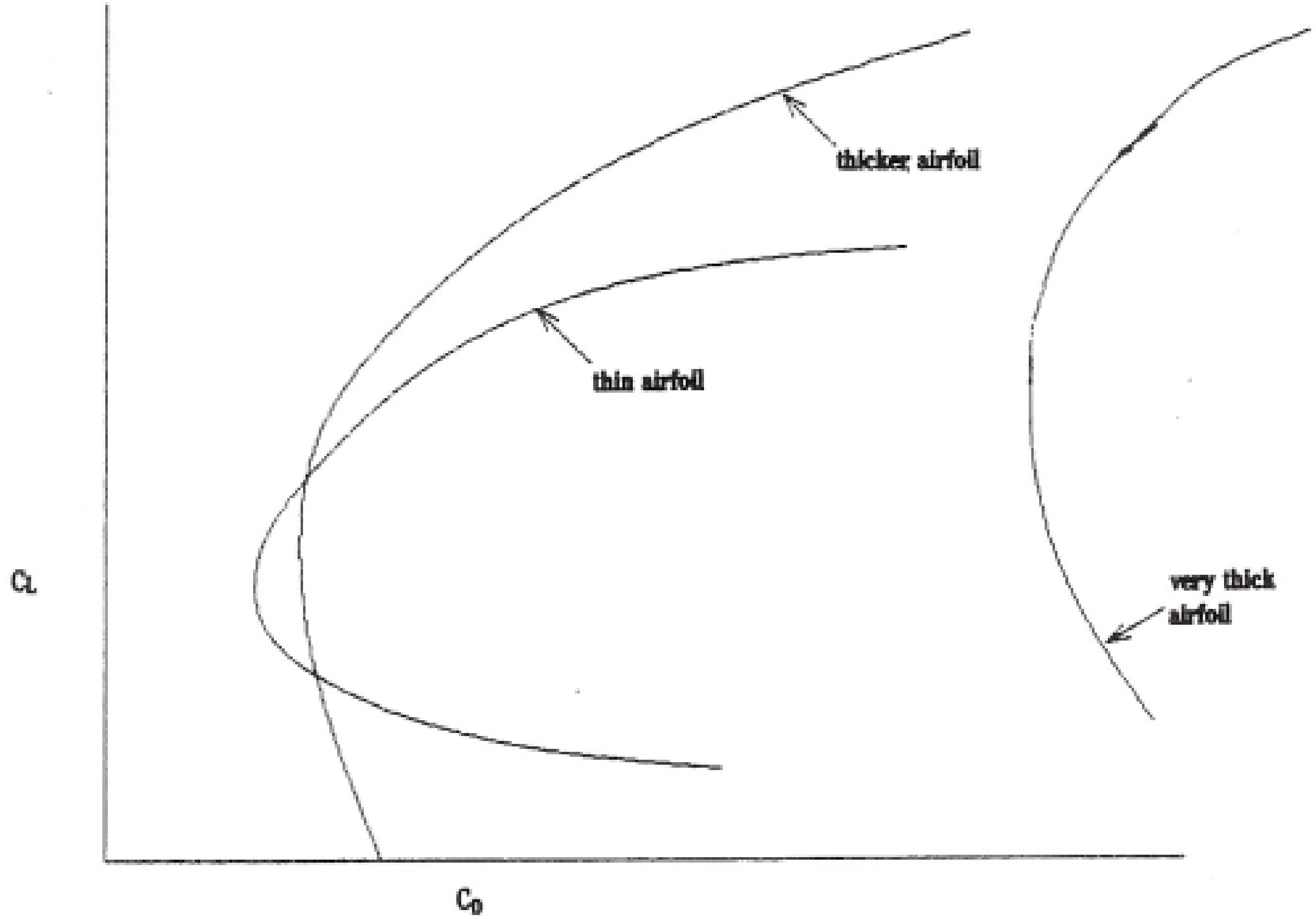


low angle of attack: flow is separated
on lower surface

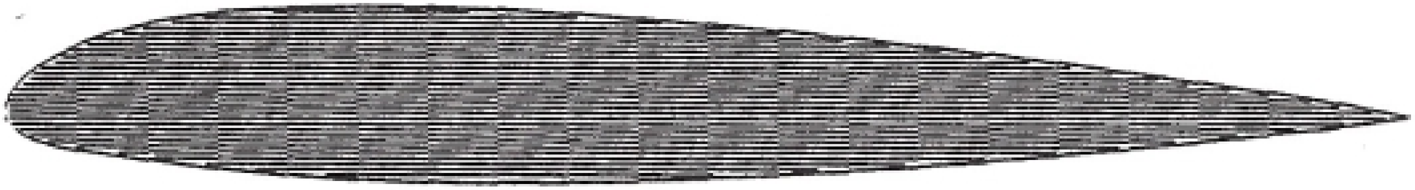
optimum angle of attack: fully attached
flow

high angle of attack: upper surface is
stalled

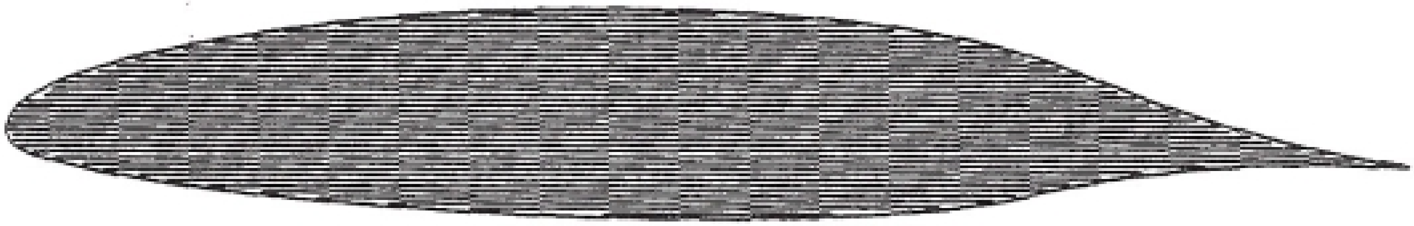
Effect of Airfoil Thickness on Drag



Typical Thickness Distributions

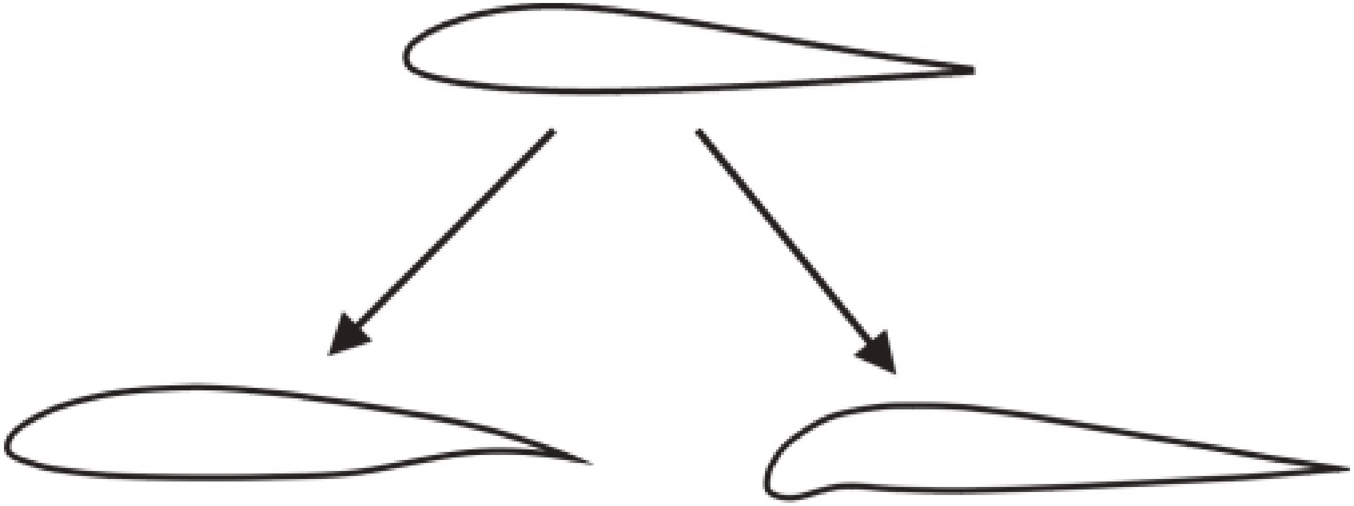


TURBULENT FLOW AIRFOIL: MAX THICKNESS FORWARD



LAMINAR FLOW AIRFOIL: MAX THICKNESS AFT

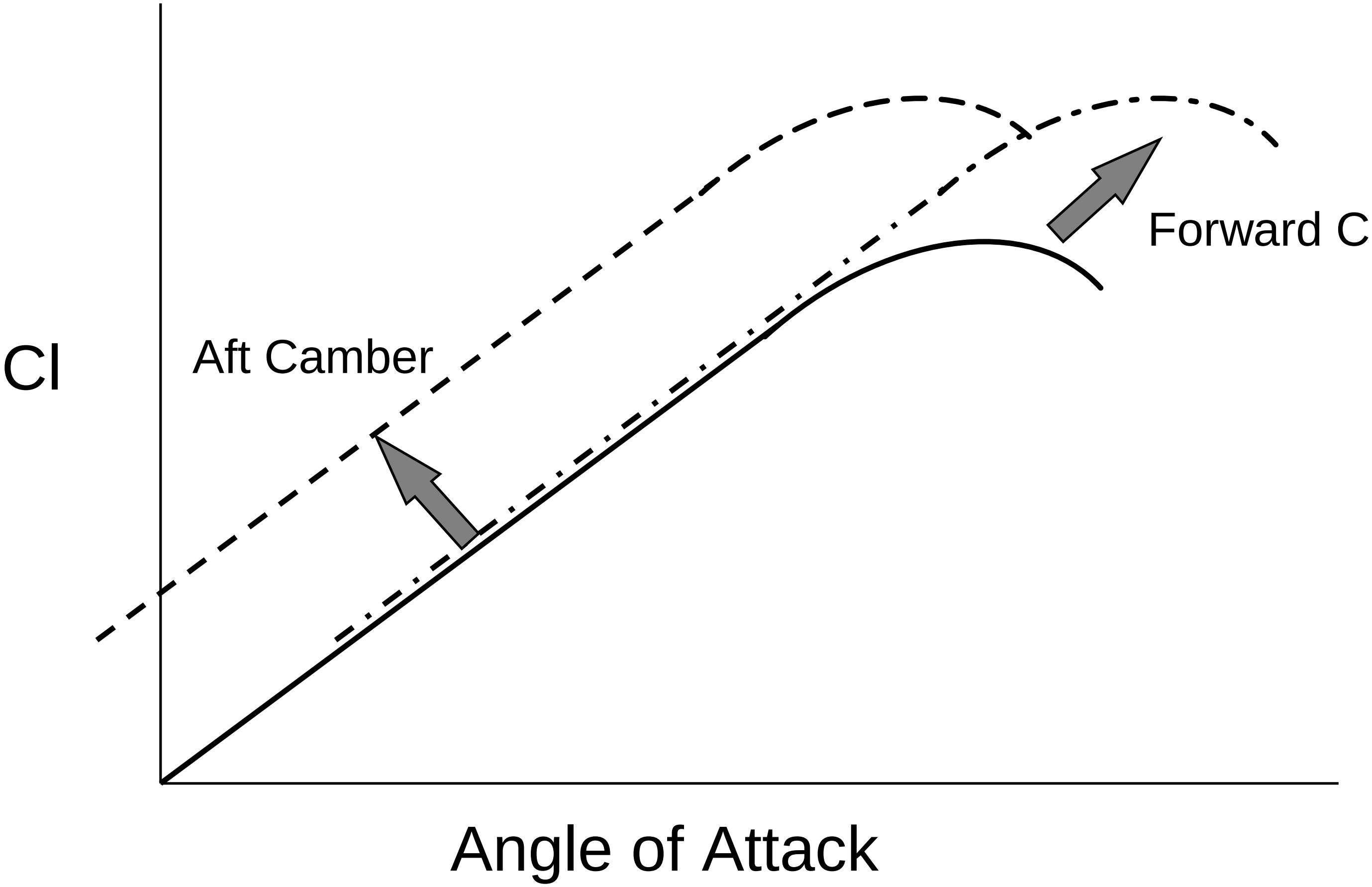
Camber Effects



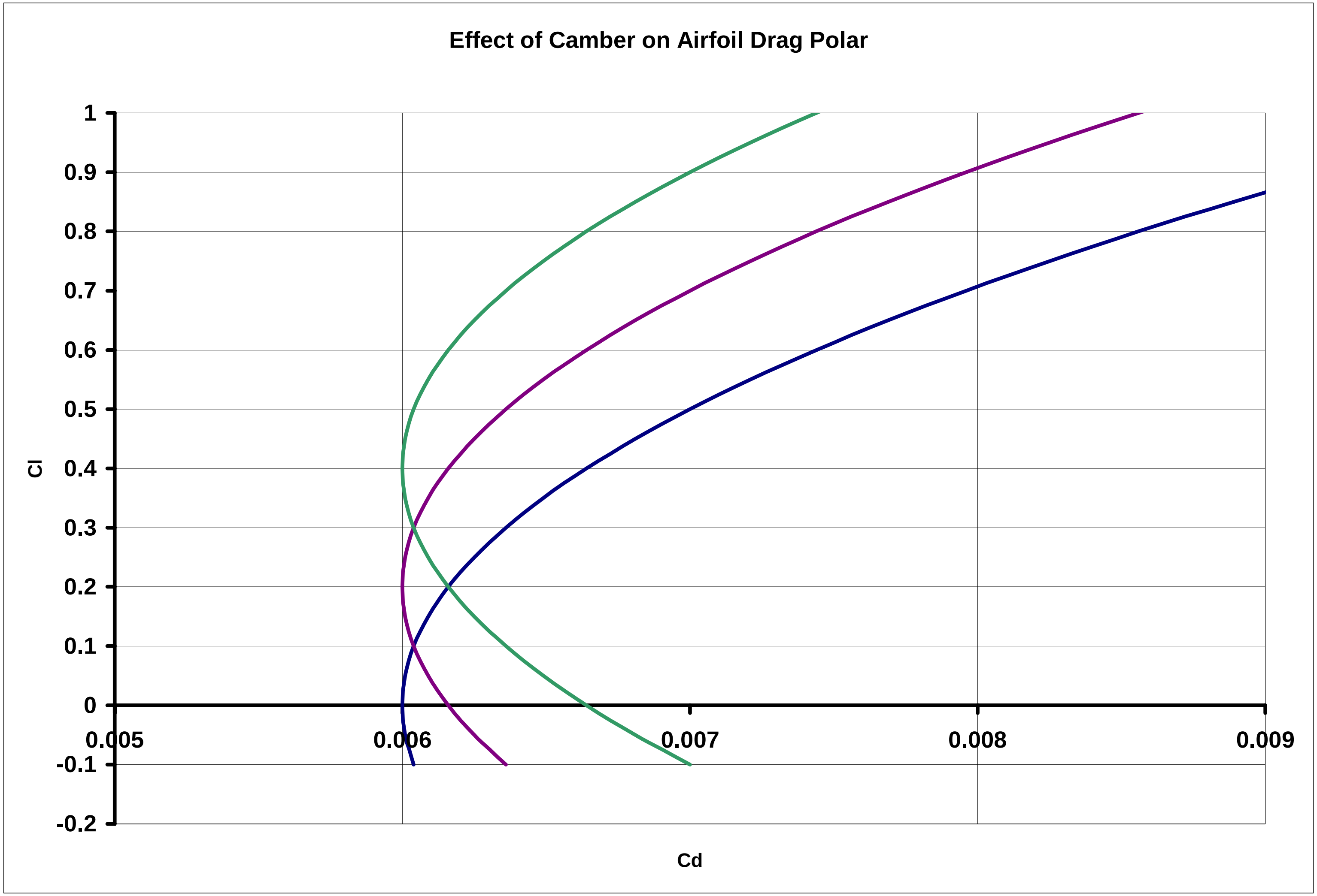
Adding aft camber increases lift at constant angle of attack. It also produces significant nose-down pitching moment that must be trimmed by downforce on the horizontal tail

Adding nose camber does not increase lift at constant angle of attack. It increases the maximum lift of the airfoil by increasing the stall angle of attack. Nose camber

Effects of Camber on Lift



Effect of Camber on Drag



3-D Wing Design

- Planform Shape
  - Taper
    - Compound Shapes or Curved Edges
  - Sweep
  - tips
  - Taper
- Wing area
- Aspect ratio
- Twist

Aerodynamic Center

- A point about which pitching moment does not vary with angle of attack.
- Typically near 25% chord for airfoils in incompressible flow
- Moves aft at transonic Mach Numbers
- AC is at 50% chord for airfoils at supersonic Mach Numbers

Span Loading

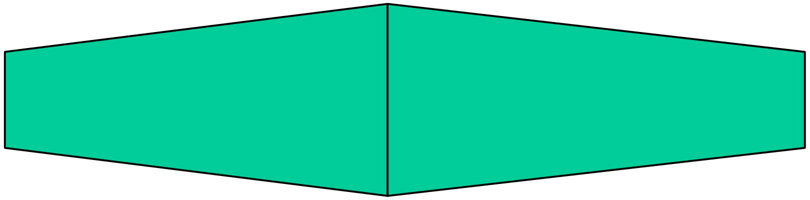
- Span loading is comprised of 2 parts: Basic, and Additional:
- Basic Span Loading:
  - Span loading when total wing lift=0
  - Primarily a function of twist and camber
  - Zero everywhere for untwisted case.
- Additional Span Loading
  - Lift due to angle of attack
  - Linear function of AOA in attached, incompressible flow
  - Primarily a function of planform (chord distribution and sweep)

Taper effects

- Positive Effects:
  - Thicker Root
  - Centroid of load moved inboard => reduced bending moment
  - Lighter Structure
  - More Volume
  - Higher Span Efficiency
- Not so Positive Effects:
  - Structural Complexity
  - High local Cl (additional) outboard
  - Reduced Reynolds number outboard
  - Poor Stall Characteristics Possible

Simple Planforms

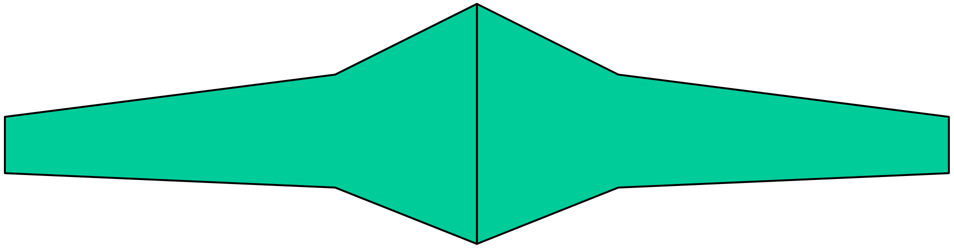
Constant Chord



Straight Taper

Compound Planforms

Constant Chord Center Section (“Semi-Tapered)



Compound Taper

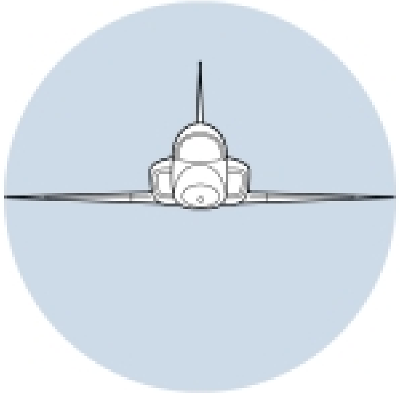
Sweep Effects:

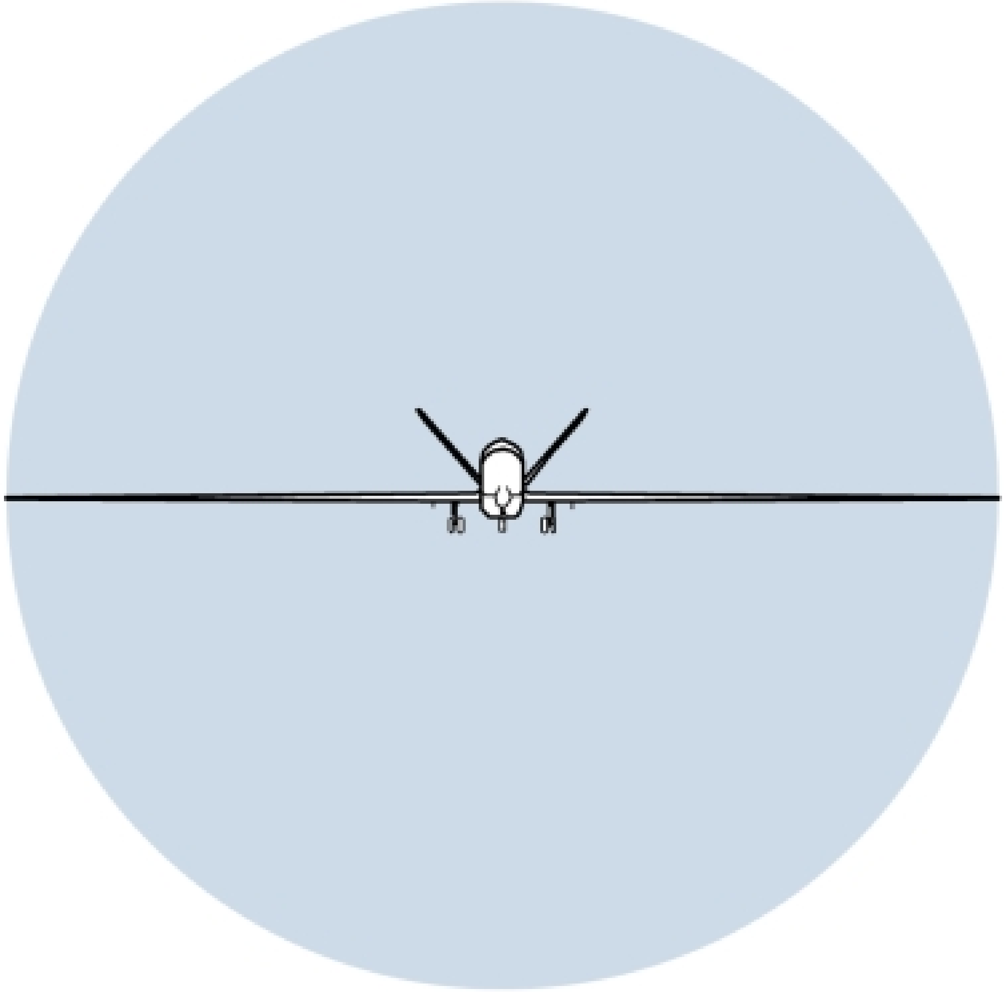
- Delayed Drag Rise
- Aerodynamic Center Moved Aft
- Heavier Structure
- Increased Additional Loading (both CLC and Cl) outboard (Decreased for forward Sweep)
- Pitch up at stall
- Aeroelastic concerns

Induced Drag
(Drag Due to Lift)

- Induced drag is determined by weight, span loading, span efficiency.
- 1/2 of the total drag at best L/D
- 3/4 of the total drag at max. endurance (min. power)
- Most important in climb and high-altitude cruise.

Induced Drag





Wing Deflects A Stream Tube of Air To Generate Lift

Stream Tube Diameter is Approximately the Wing Span

Stream Tube Size is Not Affected by Wing Chord

Induced Drag is a Function of Span Loading, Not Aspect Ratio

$$C_{di} = C_L{}^2/\Pi eAR$$

$$AR = b^2/S \quad \Rightarrow C_{di} = C_L{}^2\, S/\Pi e\, b^2$$

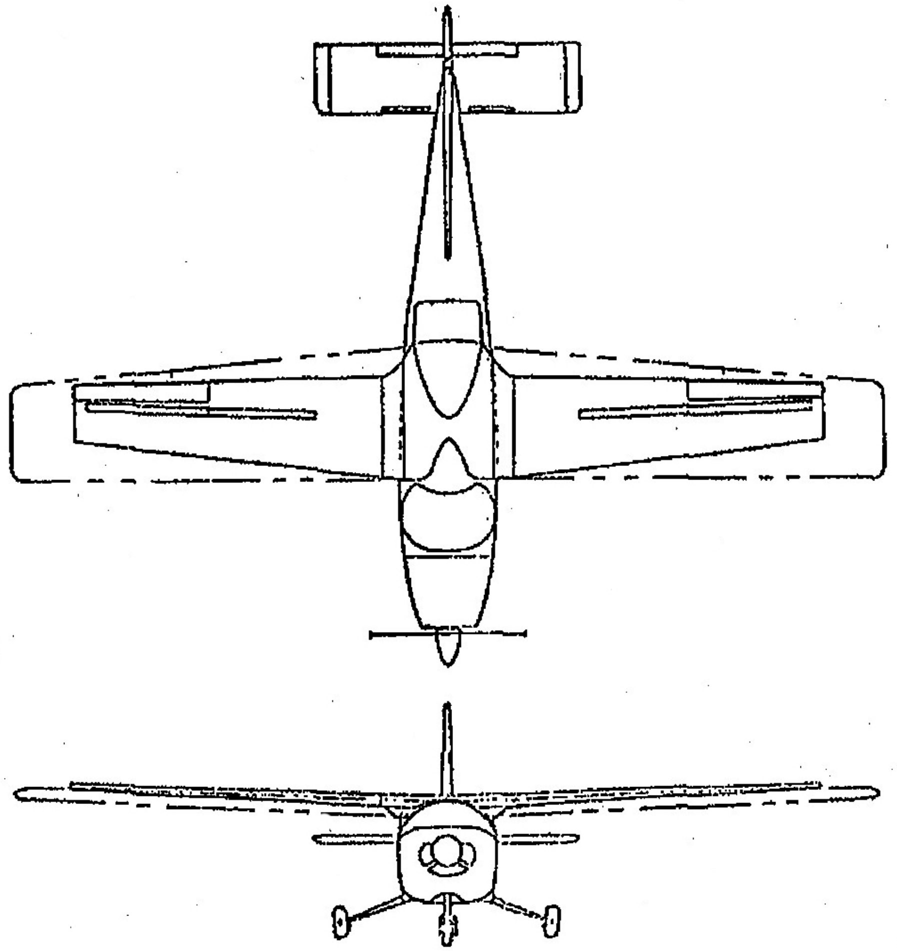
$$D_i = C_{di}\, Sq = C_L{}^2\, S^2 q/\Pi e\, b^2$$

Multiplying by q/q gives: $D_i = C_L{}^2\, S^2 q^2/\Pi e\, qb^2$

$C_L{}^2\, S^2 q^2 = L^2$ Therefore :

$$\boxed{\mathbf{D_i = L^2\, /\Pi e\, qb^2}}$$

Induced Drag Example: Redhawk



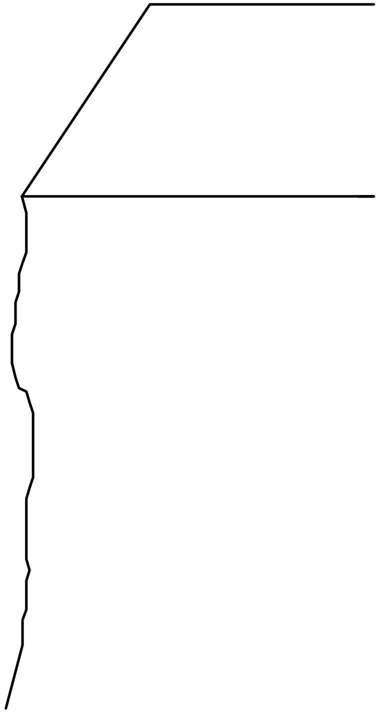
- Redhawk “Advanced Technology Light Airplane Built From Cessna Cardinal
- New Wing With “Advanced” Features
  - Higher Aspect Ratio
  - Smaller Wing Area
  - High Lift Devices
  - Spoilers for Roll Control
- New Wing Had Less Span Than Original
- Airplane Was Slower Than Stock at Cruise Altitude
- Very Poor Rate of Climb

Reducing Induced Drag

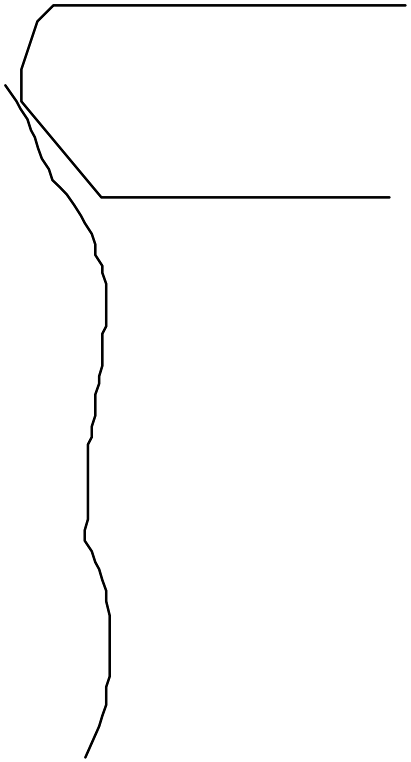
- **Reduce Weight**
- **Increase Span**
- **Increase Span Efficiency (e)**
  - **Wing Tips**
    - Some Improvement possible (~ 5%)
  - **Winglets and End Plates**
    - Induced Drag Decreased
    - Parasite Drag Increased
    - Span Extension Usually Superior
  - **Improve Wing Root Junction Flow**
    - Poor Junction causes large loss of span efficiency

Wing Tips

Advancing tip:
Vortex sheds outboard



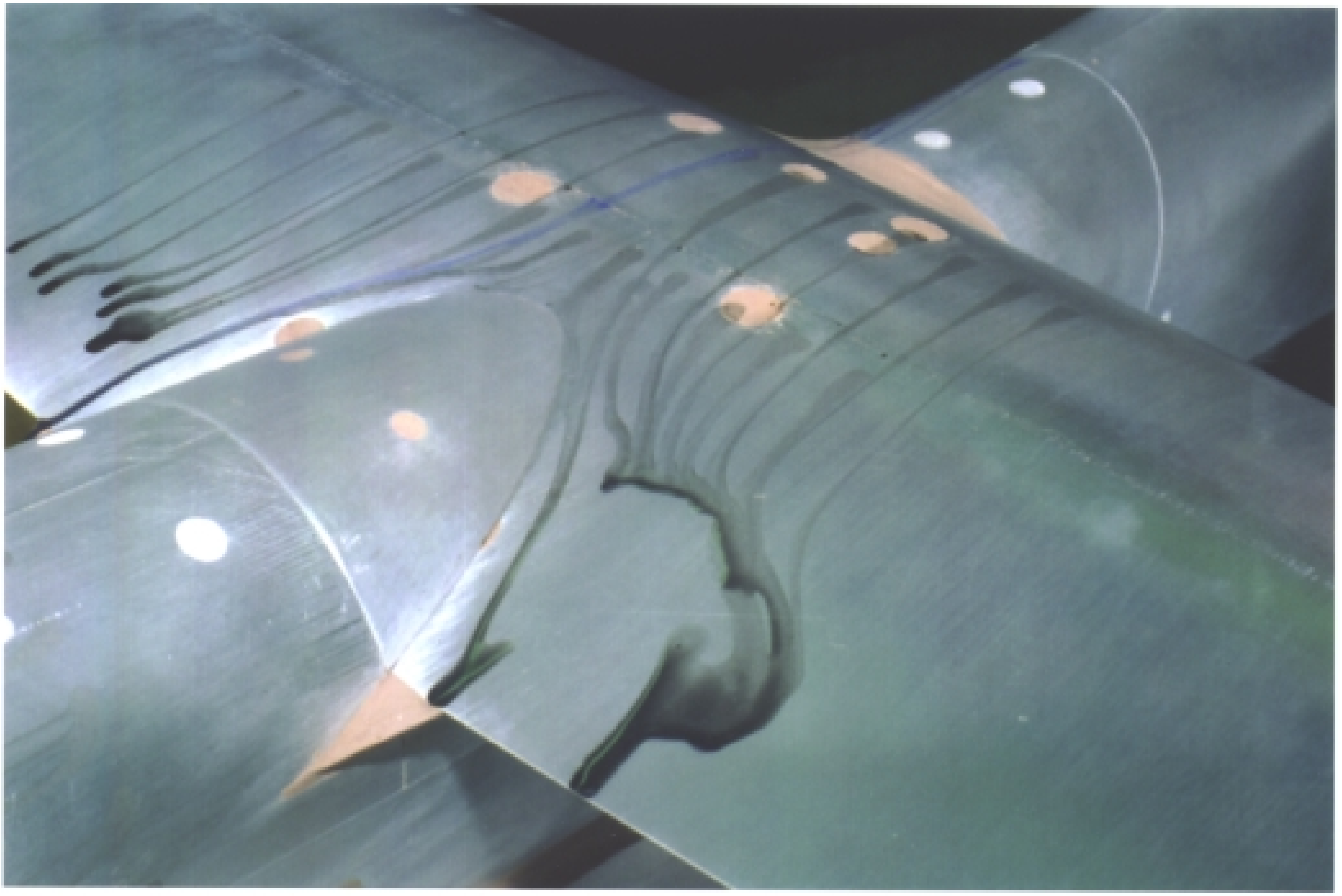
Retreating tip:
Vortex sheds inboard



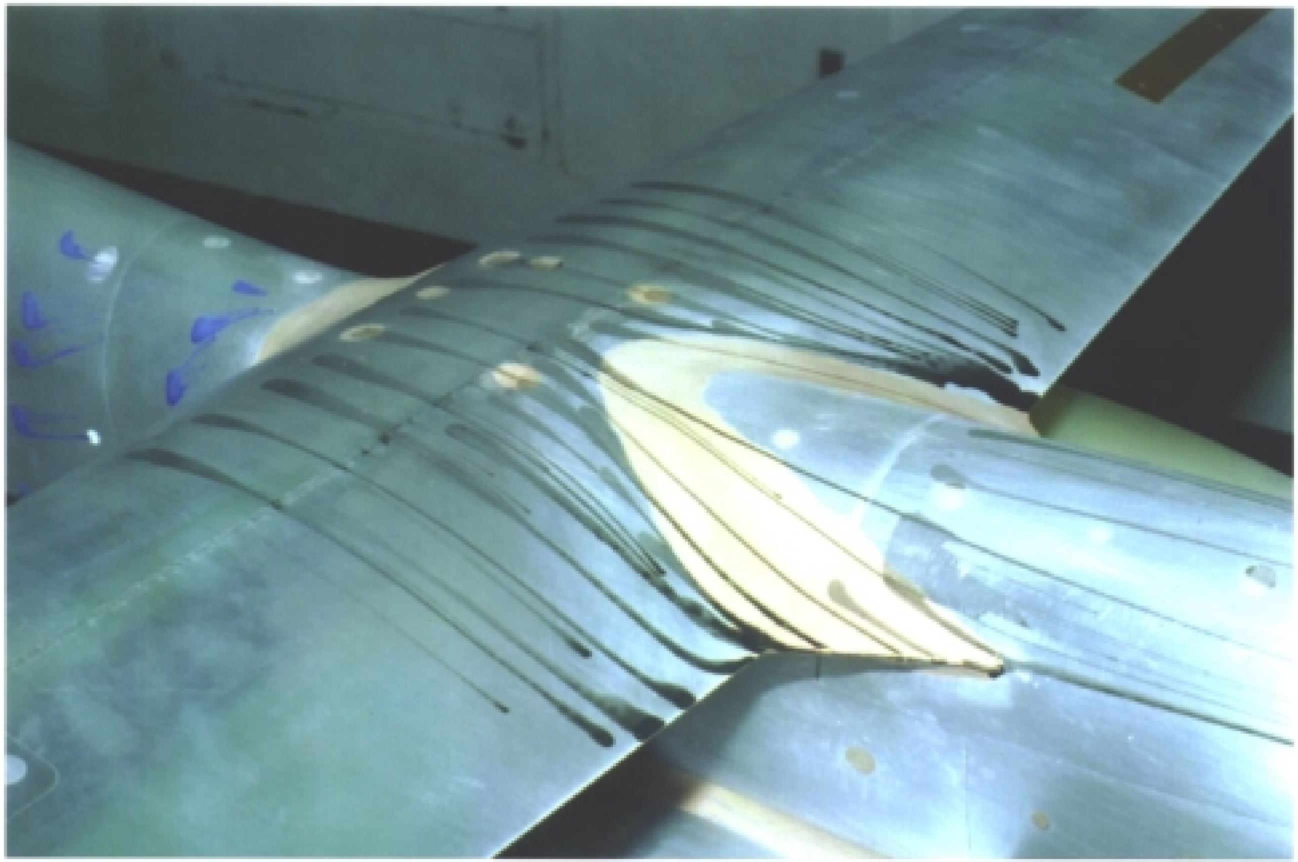
Wing Root Junctions

- Air can get very confused
- Local separation / vortex shedding common
- A bad wing root junction increases *both* parasite drag and induced drag
- Fillets and fairings
- Body shaping

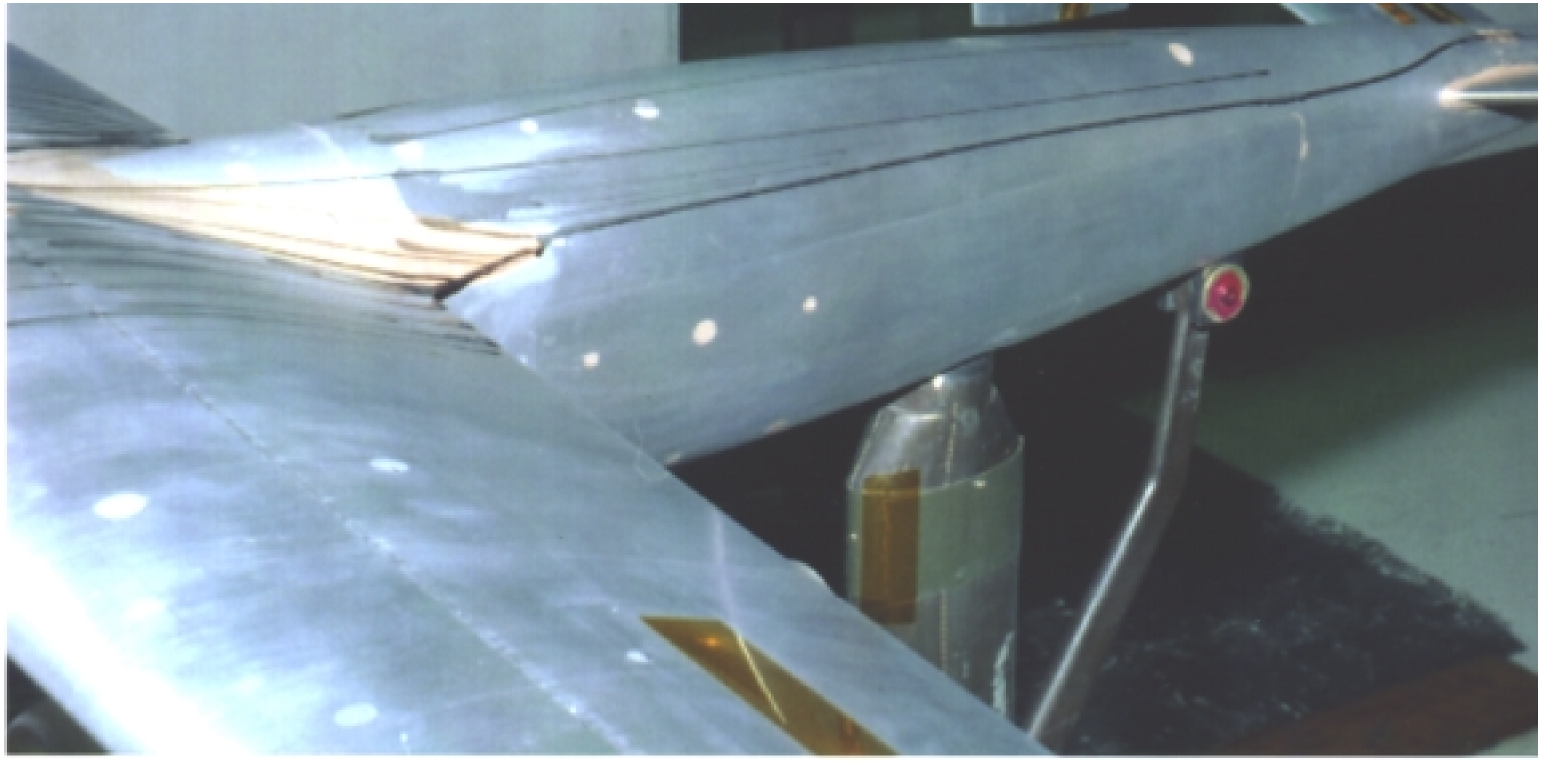
Flow Separation at a Wing Root



Improved Junction Fairing Eliminates Separation



Fully Attached Flow



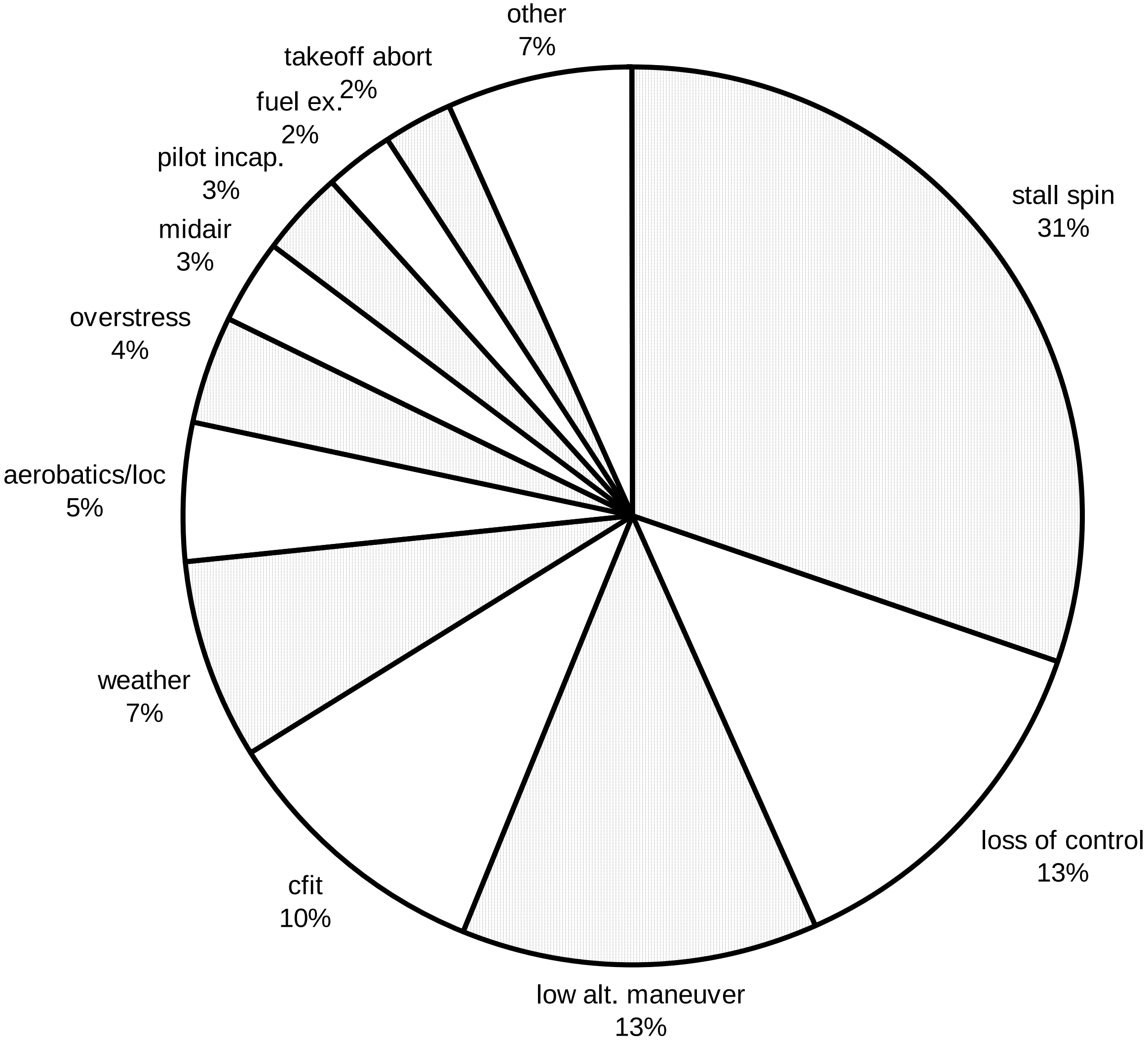
Stalls and Spins

- Stalls:
  - What is a stall?
  - Effect of angle of attack
  - Effect of load factor
  - Airfoil Effects
  - 3D Effects
  - Airplane Stall Characteristics

Stalls and Spins

- Stall/spin accidents are still a major problem.
- Airplane should have good stall warning
- Gentle stall characteristics are important for the average pilot’s safety.
- Spin resistant configurations are desirable
- Good low-speed flying qualities are important to stall/spin avoidance

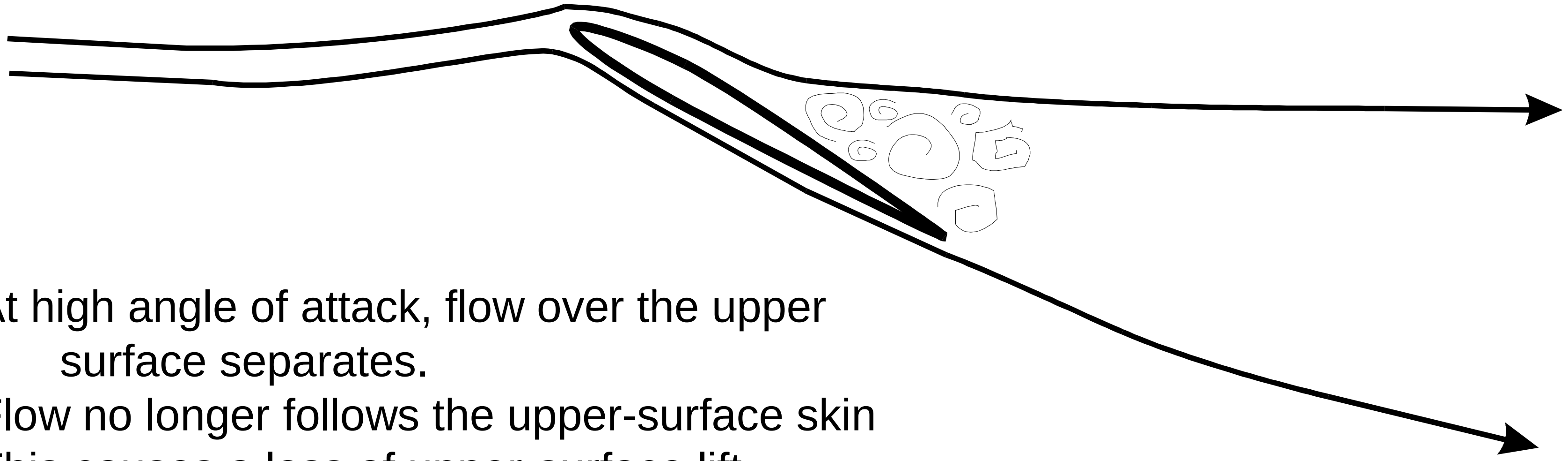
Pilot Induced Fatal Accidents (1994-1998)



Stall

- Stall is a loss of lift caused by flow separation on the upper (low-pressure) surface of the airfoil.
- Stall is affected by:
  - Airfoil Geometry
  - Planform
  - Wing Twist
  - Reynolds Number
  - Mach Number
- For any given geometry, stall is determined by angle of attack.

- At low angles of attack, the airflow over an airfoil is attached
- The flow follows the contours of the skin
- Lift varies linearly with angle of attack



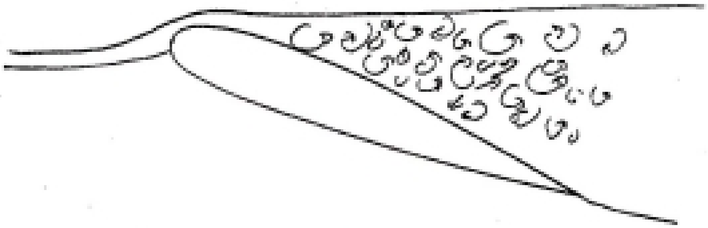
- At high angle of attack, flow over the upper surface separates.
- Flow no longer follows the upper-surface skin
- This causes a loss of upper-surface lift
- When the separated region gets large enough the airfoil is stalled.

Types of Airfoil Stall

Leading Edge Stall

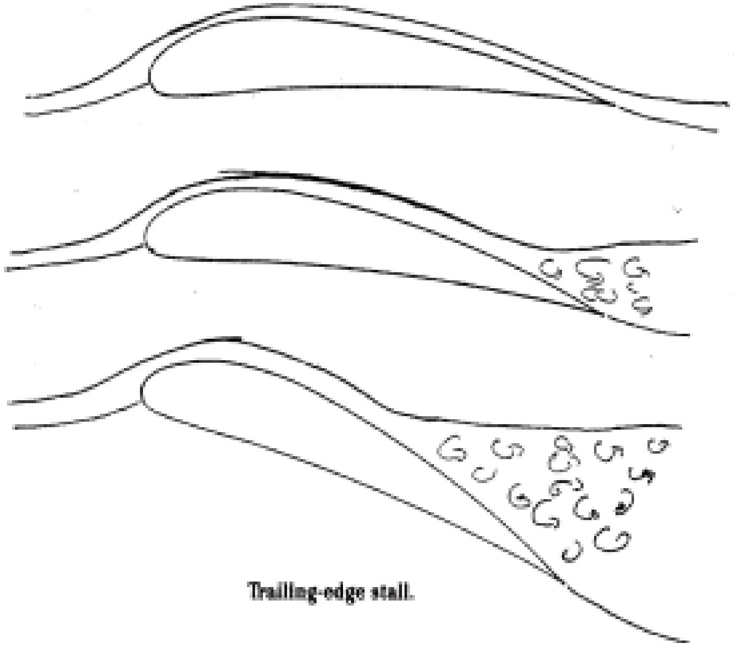
1) attached flow

2) separation bubble forms



3) bubble bursts, stalling entire upper surface

Trailing Edge Stall



Trailing-edge stall.

Wing Stall Progression

- Wing will stall first where local lift coefficient first exceeds local C_{lmax}
- Stall should start inboard of about 1/3 of the exposed semi span for acceptable roll damping at stall.
- Stall should develop progressively from root to tip

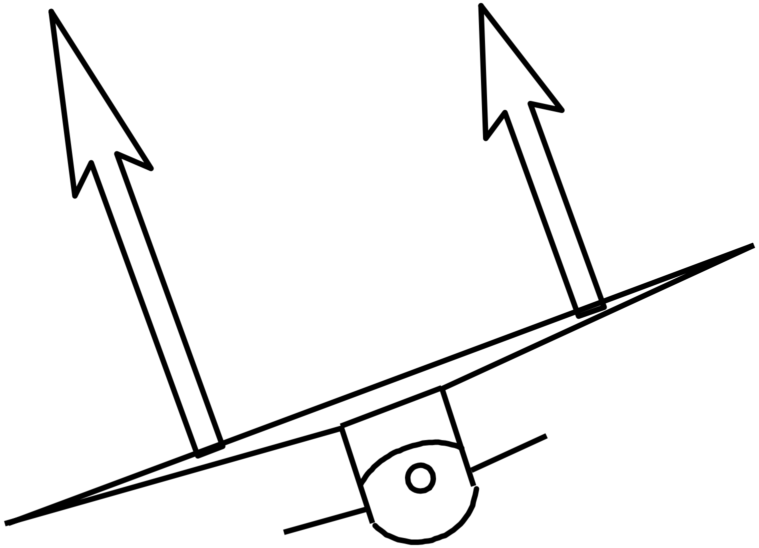
Wing Twist

- Washout if tip is at lower AOA than root
- Wash-in if tip is at higher AOA than root
- Washout is used to control the spanwise development of the stall.
  - Amount of washout needed depends on planform
    - Highly tapered wings need more twist
- Insufficient washout can cause dangerous roll-off at the stall
    - Attempting to reduce drag by eliminating washout is likely to be dangerous

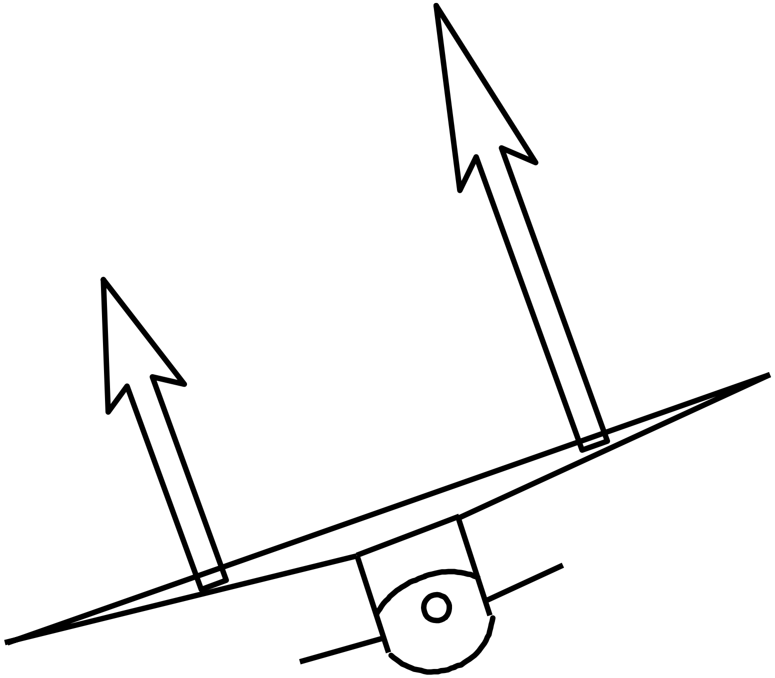
WING WASHOUT OMITTED

- Why do they do it?
  - Perception that wing twist increases drag and eliminating washout will make the airplane faster.
- But its a misconception:
  - Washout actually has very little effect on parasite drag.
  - Removing twist may actually hurt span efficiency and increase drag.
- Danger:
  - Airplane is likely to have dangerous stall/spin behavior.

Roll Damping

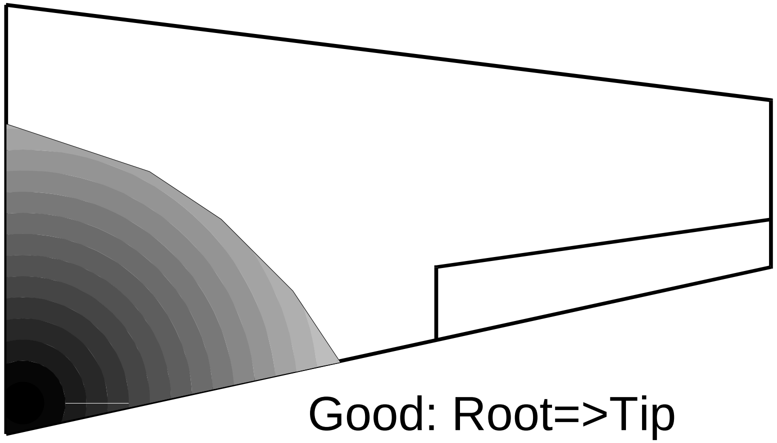


Stable: Lift change opposes roll

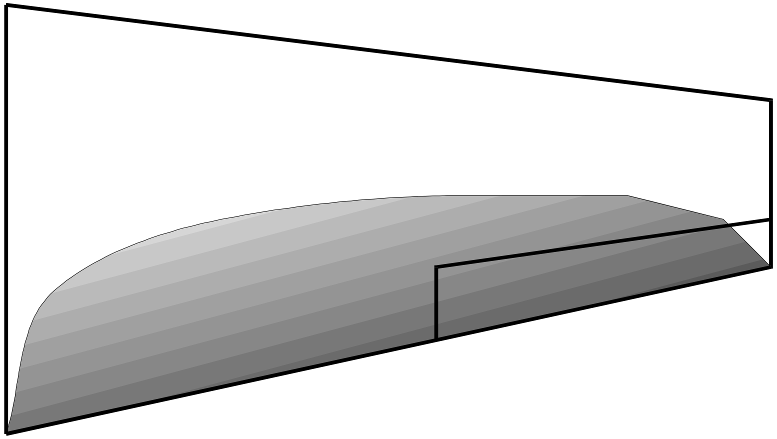


Unstable: Lift change drives roll

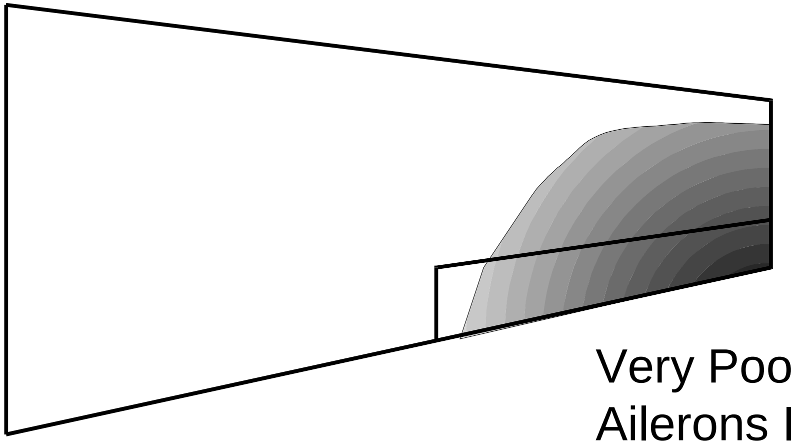
Stall Progression on Wing:



Good: Root=>Tip
Ailerons effective
Stable Roll Damping



Poor: Full-Span
Sudden Stall
Ailerons Weak
Roll-off Likely



Very Poor: Tip => Root
Ailerons Ineffective
Unstable Roll Damping
Spin likely

Spin Resistance

Angle of Attack Limiting

Discontinuous Leading Edge Cuffs