Forces

- On takeoff roll there is an unbalance of forces (thrust is greater than drag) causing the airplane to accelerate
- The faster the aircraft goes, greater lift is created and eventually there is enough lift on the wing to take off
- During ascending flight, if the aircraft is maintaining a constant true airspeed, all the forces are balanced. This is true for straight and level flight as well as climbs and descent.
- No change is airspeed means no acceleration.
- As the air density changes, climb angle will change, which changes the vertical velocity, which results in acceleration or deceleration

Density Altitude

- Air density given as a height above mean sea level
- Is pressure altitude (altimeter) corrected for nonstandard temperature

$$\mathrm{DA} = \frac{T_{\mathrm{SL}}}{\gamma}\left[1 - \left(\frac{P/P_{SL}}{\mathrm{T}/T_{SL}}\right)^{\frac{\Gamma R}{gM - \Gamma R}}\right]$$

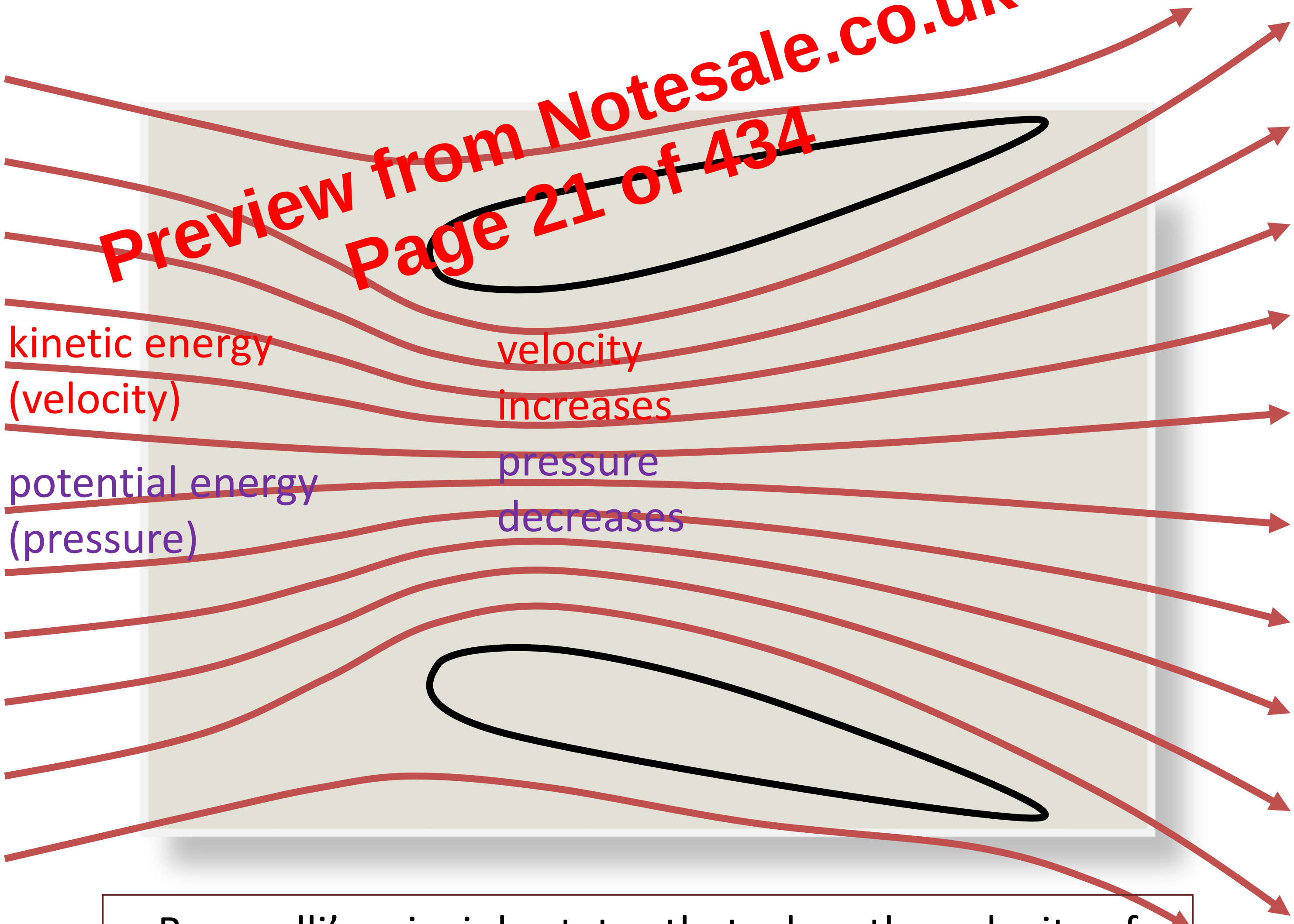
- **As OAT increases, air density decreases and DA increases**

- DA affects
  - lift (reduction in air density reduces the wing's lift)
  - efficiency of propeller or rotor (an airfoil) similar to lift on wing
  - power output of engine (less oxygen at altitude) which is reduced at altitude and influenced by moisture in air

See Exercise 2, Question 5 on how to calculate Density altitude!

The Venturi Tube and Bernoulli's Principle

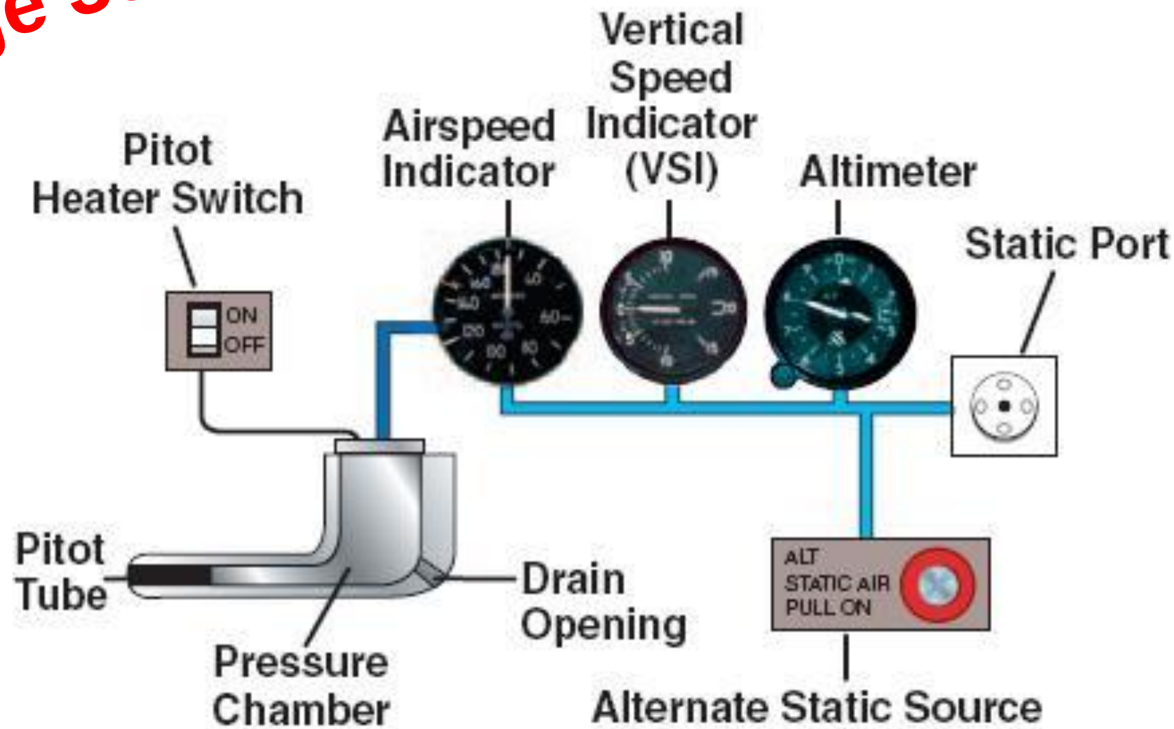
Giovanni Battista Venturi (late 1700's), Italian physicist



Bernoulli's principle states that when the velocity of airflow **INCREASES**, it's pressure **DECREASES**.

Pitot Static System

- The pitot tube is mounted facing forward with static pressure detected at ports on one or both sides of the aircraft. Sometimes both pressure sources are combined in a single probe, a pitot-static tube.



Total pressure = Static pressure + Dynamic pressure

Static pressure: Static ports

Dynamic pressure: Pitot tube

Equivalent Airspeed

- At standard sea level pressure, **calibrated airspeed** and **equivalent airspeed** are equal. Up to 200 knots CAS and 10,000 ft (3,000 m), the difference is negligible, but at higher speeds and altitudes CAS must be corrected for compressibility error to determine EAS.
- The significance of equivalent airspeed is that, at mach numbers below the onset of wave drag, all of the aerodynamic forces and moments on an aircraft are proportional to the square of the equivalent airspeed.
- EAS is closely related to IAS shown by the airspeed indicator. Handling and 'feel' of an aircraft, and the aerodynamic loads upon it, at a given EAS, are very nearly constant and equal to those at standard sea level without respect to actual flight conditions.

About EAS

- EAS is also called the "perfect IAS"
- If the airspeed system worked perfectly, it would always display EAS
- The only difference between EAS and TAS is density (temperature)
  - Sophisticated systems use the Rosemont temperature probe and computer to calculate temperature ram rise friction (without temperature input, there is no TAS reading)

True Airspeed

- TAS is speed of the aircraft relative to the atmosphere
- TAS and heading of an aircraft constitute its velocity relative to the atmosphere. The vector relationship between TAS and speed with respect to the ground is: $V_t = V_g - V_w$
- Where

V_w = windspeed vector

True Airspeed

- If there is no wind, TAS = GS
- As air becomes less dense (e.g., climbing), TAS will increase for the same EAS
- Mach number expresses how fast TAS is in relation to speed of sound under those atmospheric conditions (mach 1 + SOS)

Continuity Equation

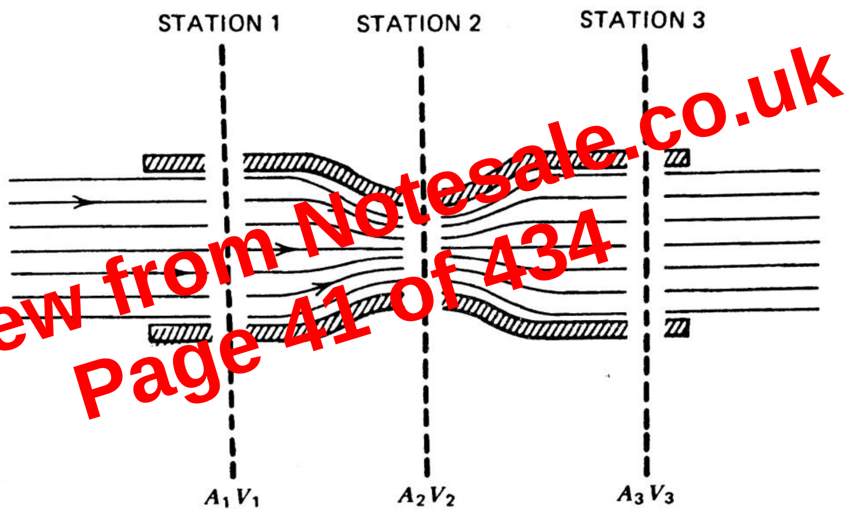


Fig. 2.1. Flow of air through a pipe.

The continuity equation states that the mass airflow is a constant:

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 = \rho_3 A_3 V_3 = \text{constant} \qquad (2.7)$$

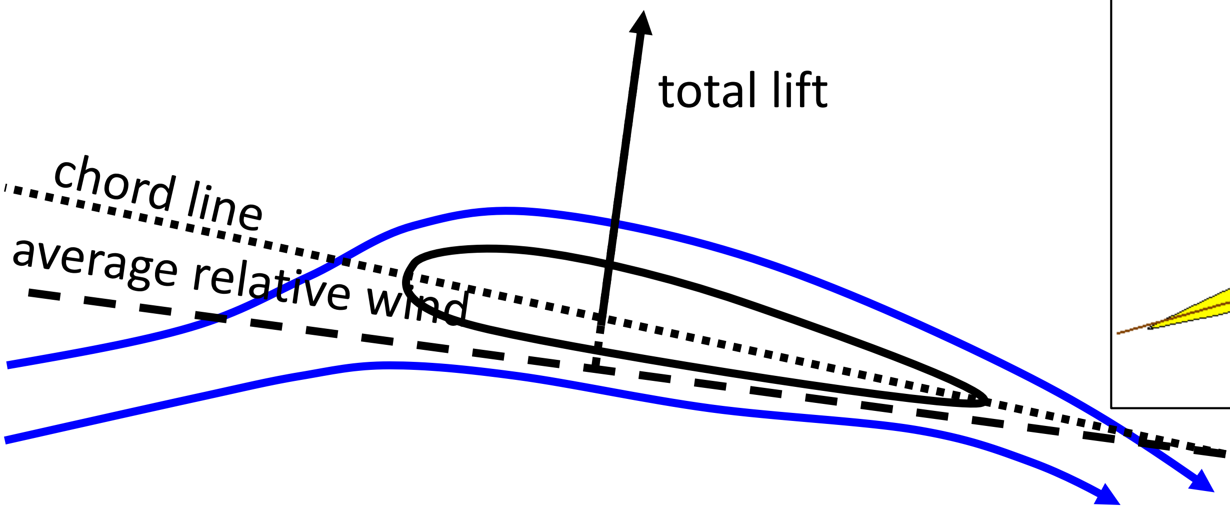
- The equation states that mass air flow, Q, is constant.
- In subsonic flight, air density is not compressed, and therefore is regarded as constant.
- In transonic and supersonic flight, air density is compressed and is regarded as dynamic.

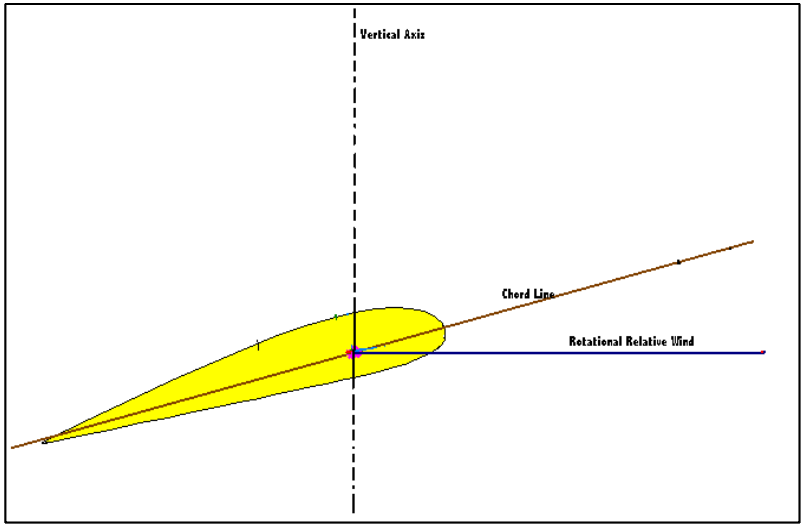
Angle of Attack

Angle of Attack (AOA or α): Angle between the average relative wind and chord line of the airfoil

- The angle of attack is the angle between the chord line and the average relative wind.
- Greater angle of attack creates more lift (up to the $C_{L\,Max}$ point, where the airfoil produces maximum lift, exceeding that results in a stall).

Center of Pressure: Point on the chord line where the Aerodynamic Force acts



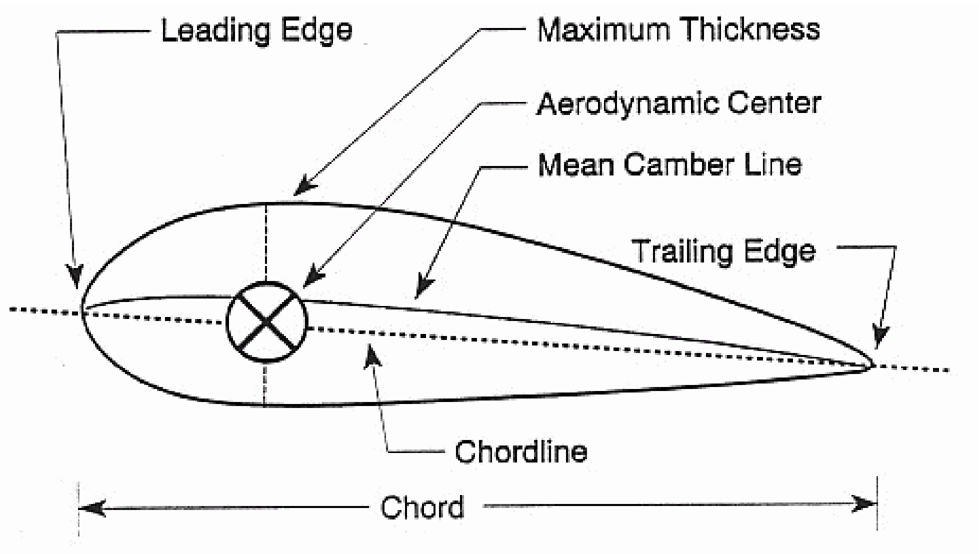


Aerodynamic Center (AC)

Defined: 1. Point along the chord line around which all changes in the aerodynamic force take place

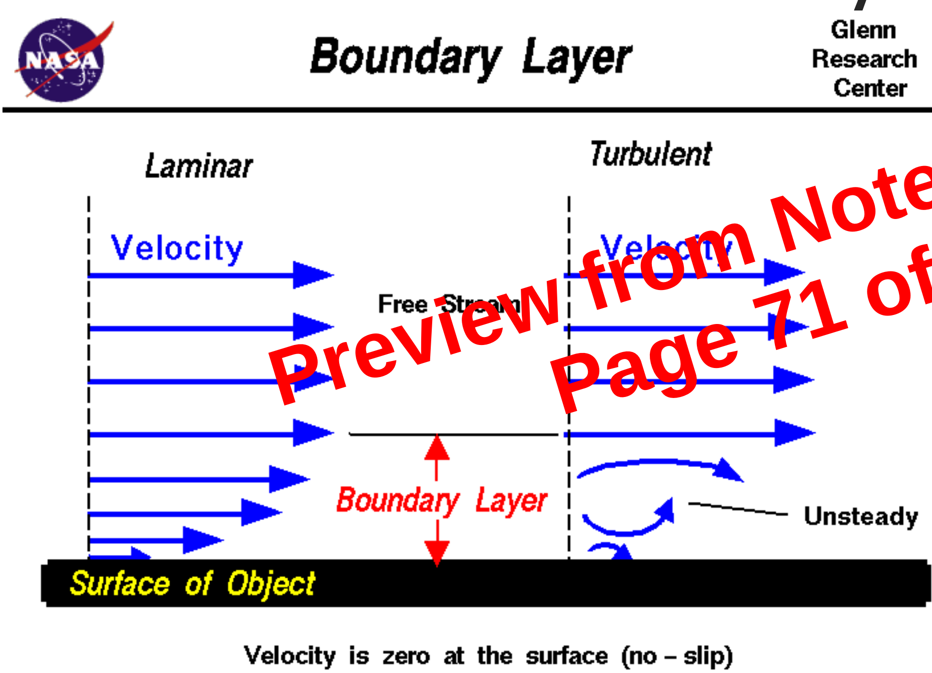
2. Location (x_{ac}) about which the pitching moment does not change with angle of attack

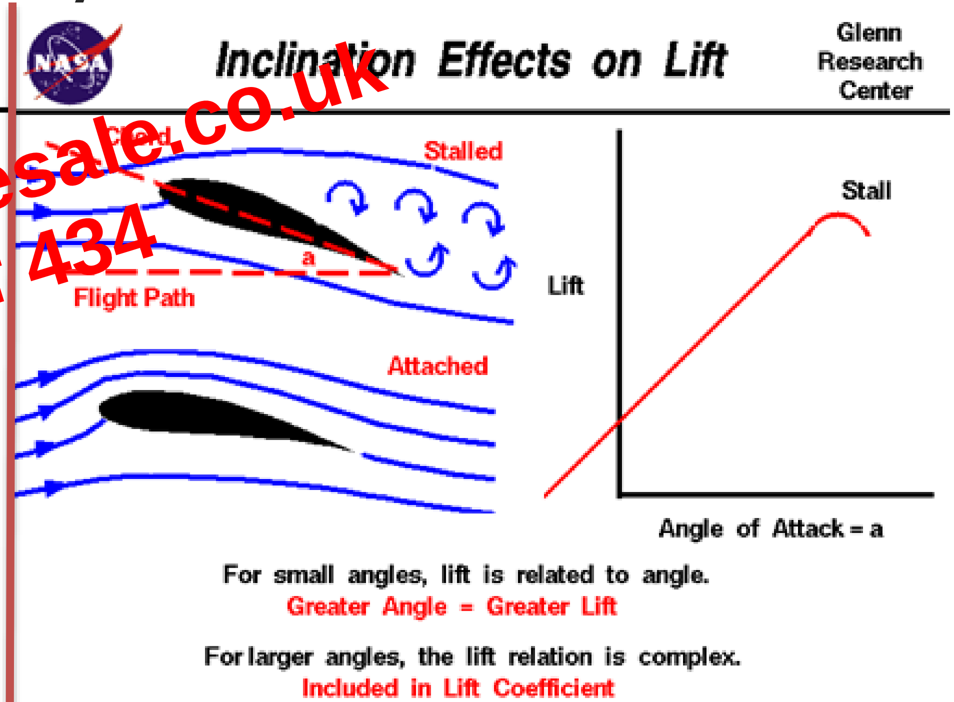
****On a subsonic airfoil, the AC is located approximately one-quarter (between 23% - 27%) of the chord line from the leading edge****



AC will remain **mostly stationary** unless airflow over wings approaches speed of sound (moves to about 50% chord)

Boundary Layer and Lift





Similarity Parameters

Glenn Research Center

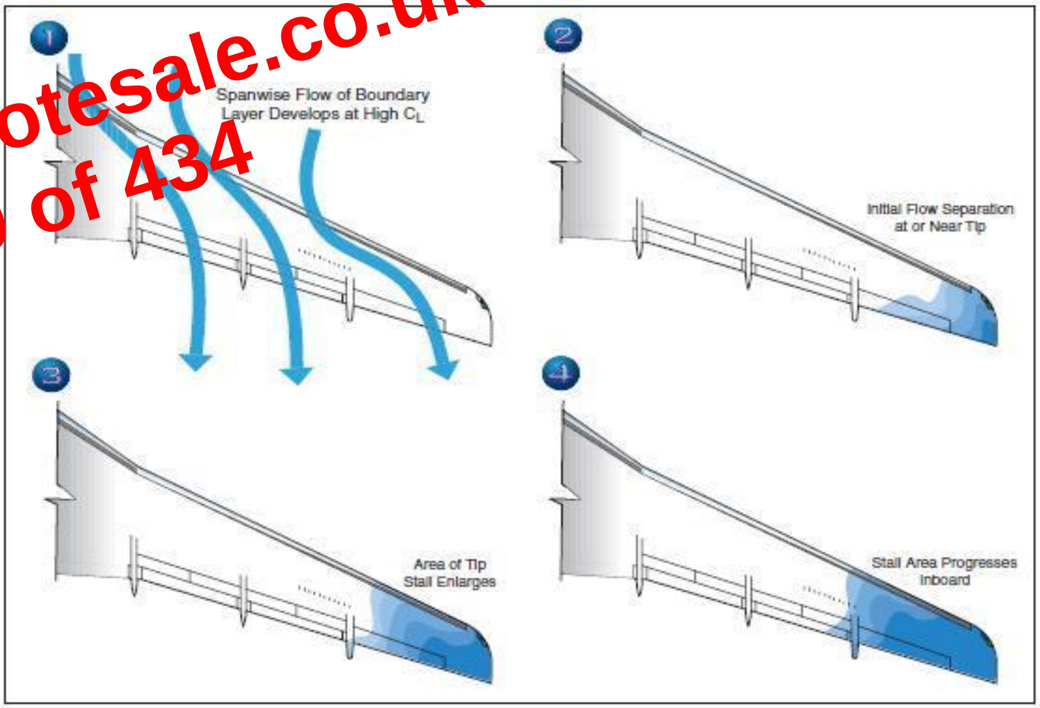
	Viscosity	Compressibility
Characteristic	"Stickiness"	"Springiness"
Parameter	Reynolds (Re)	Mach (M)
Definition	density x velocity x length / viscosity coefficient	flow velocity / speed of sound
Equation	$\frac{\rho \times V \times L}{\mu}$	$\frac{V}{a}$

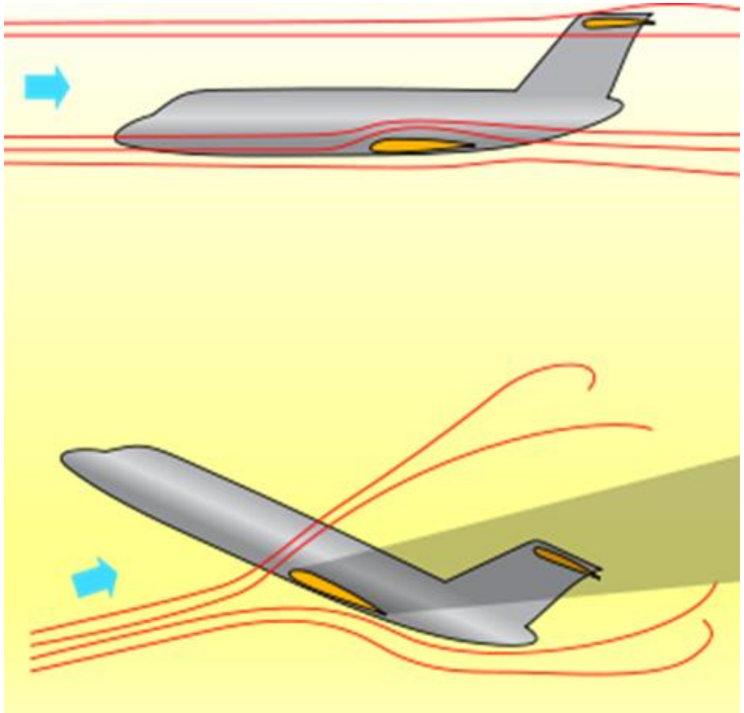
Aerodynamic Forces depend on Re and M

For a valid experiment, Reynolds Number and Mach Number must match flight conditions.

Stall

- Wing tip stall increases with wing taper or sweep

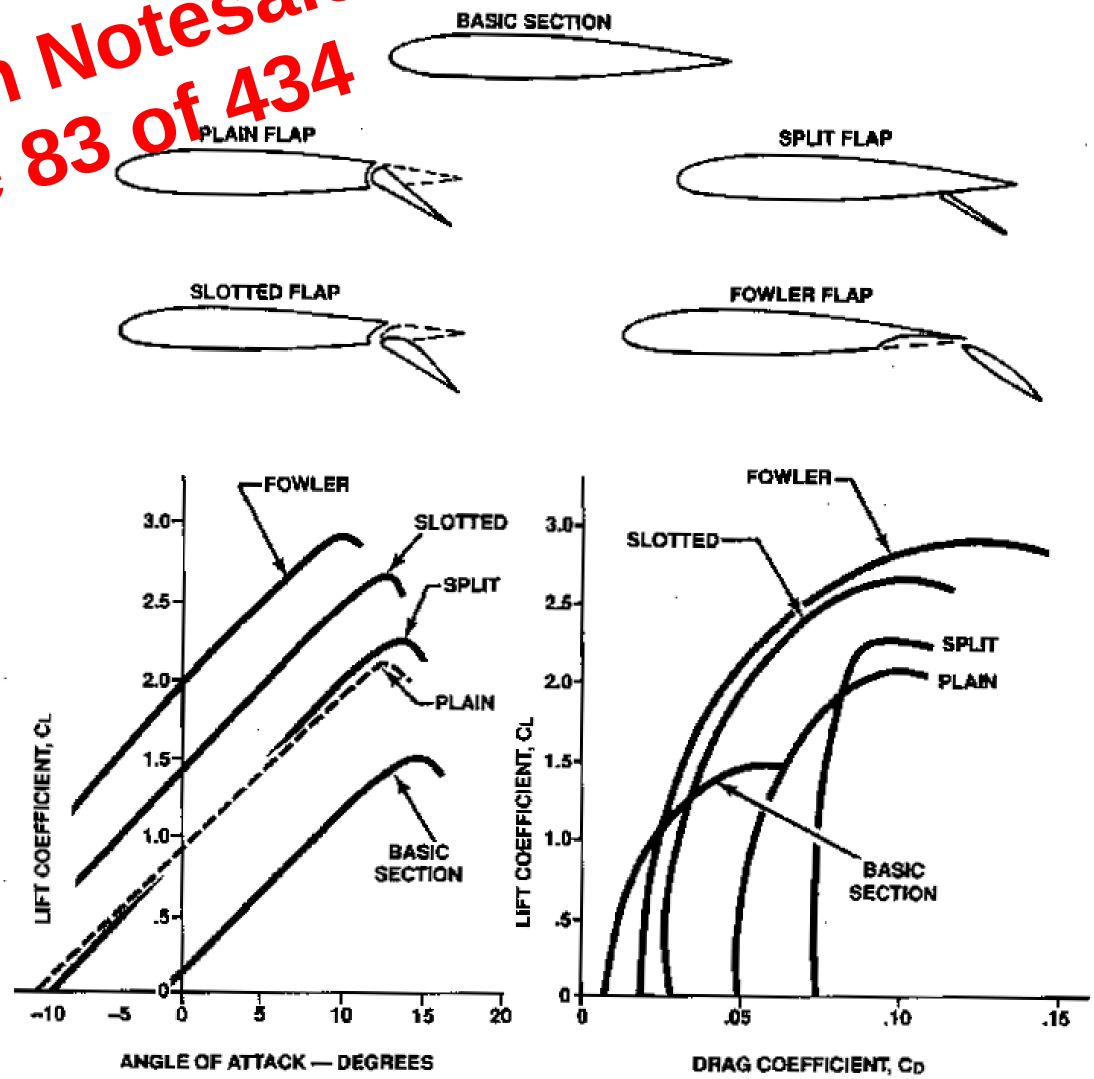




- Deep Stall:
  T-tail is more at risk

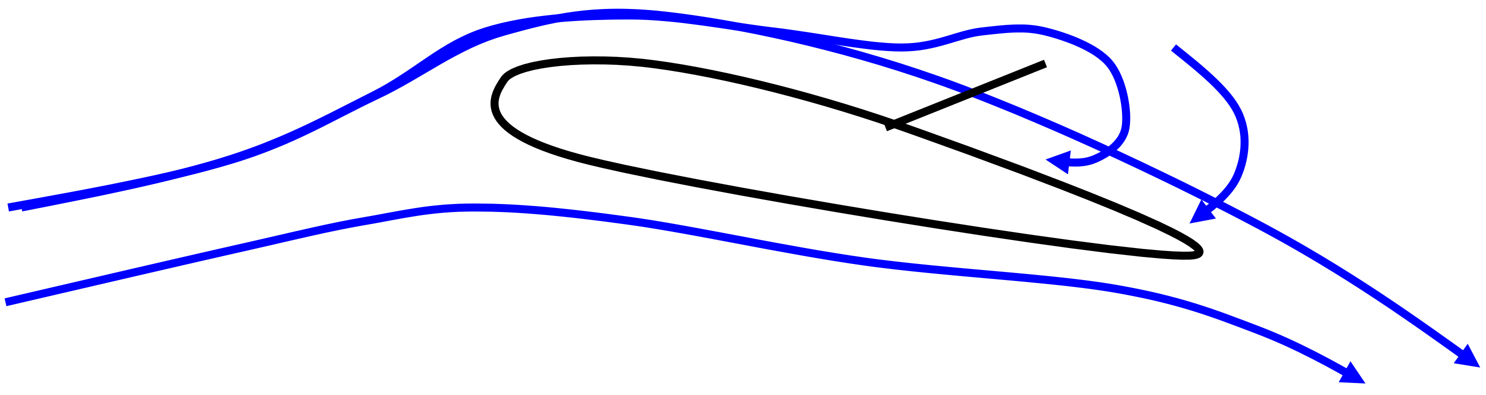
Got Lift? Flaps

- Flaps increase the wing's camber.
  - Some also increase the wing area (fowler flap).
- Almost all jet transports also have leading edge flaps.



Too Much Lift? Spoilers

- Spoilers destroy lift:
  - to slow down in flight (flight spoilers);
  - for roll control in flight (flight spoilers);
  - to slow down on the ground (ground spoilers).



Vortex Generator

- Vortex generators modify the boundary layer
- Flow in the boundary layer can be laminar or turbulent
- Surface air adheres and slows, added layers slow less
- Laminar air flows freely and is orderly and stable
- Back from the leading edge is a transition region where boundary layer becomes turbulent
- Despite the turbulence, on the wing surface, there is still a thin laminar sub-layer with no turbulence
- This is due to the dampening effects of viscosity
- The sub-layer slows and becomes the cause of separation and reverse flow, causing the wing stall

Wingtip Vortices

- High pressure air at stagnation point (leading edge) flows spanwise (toward tip)
- At tip, flows around and to upper surface and adds to downwash
- Downwash doubles
- Circular motion results in wingtip vortices

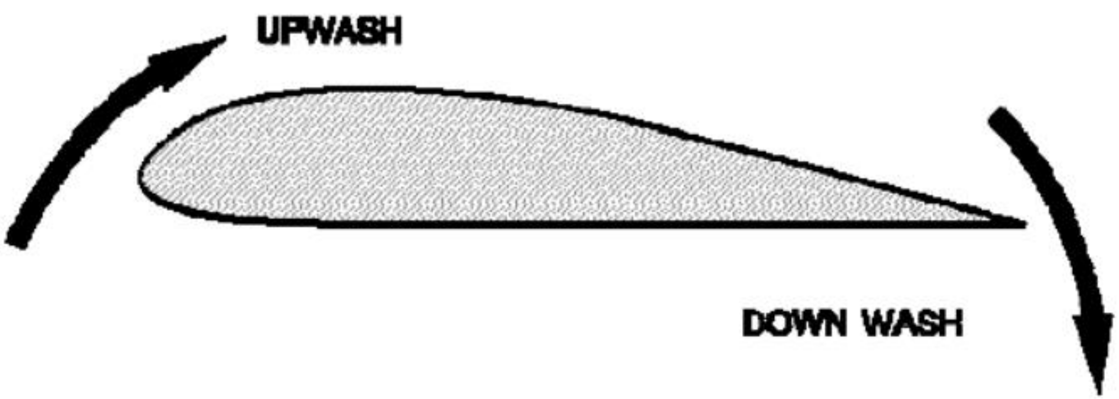


Figure 1-5-7 Upwash and Downwash

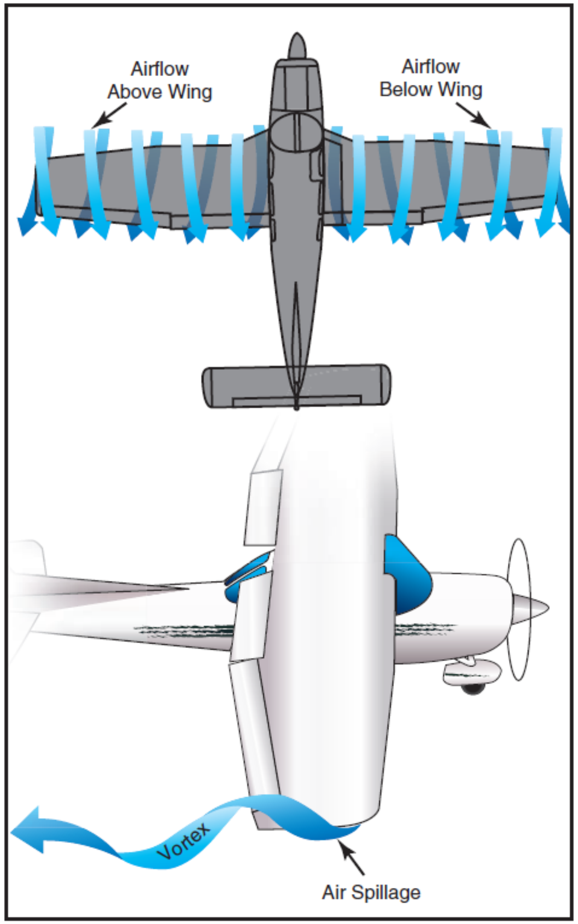


Figure 3-4. Wingtip vortices.

Planform effects and Induced drag,

Lecture 7

Swept Wing Span

- Span in a straight wing is the distance between two wing tips parallel to the aircraft's lateral axis (y-axis)
- With a swept wing, span is twice the distance between one wing tip to the fuselage center line parallel to the 50 % sweep chord line
- Wing sweep angle alters wing span to an effective span which is smaller

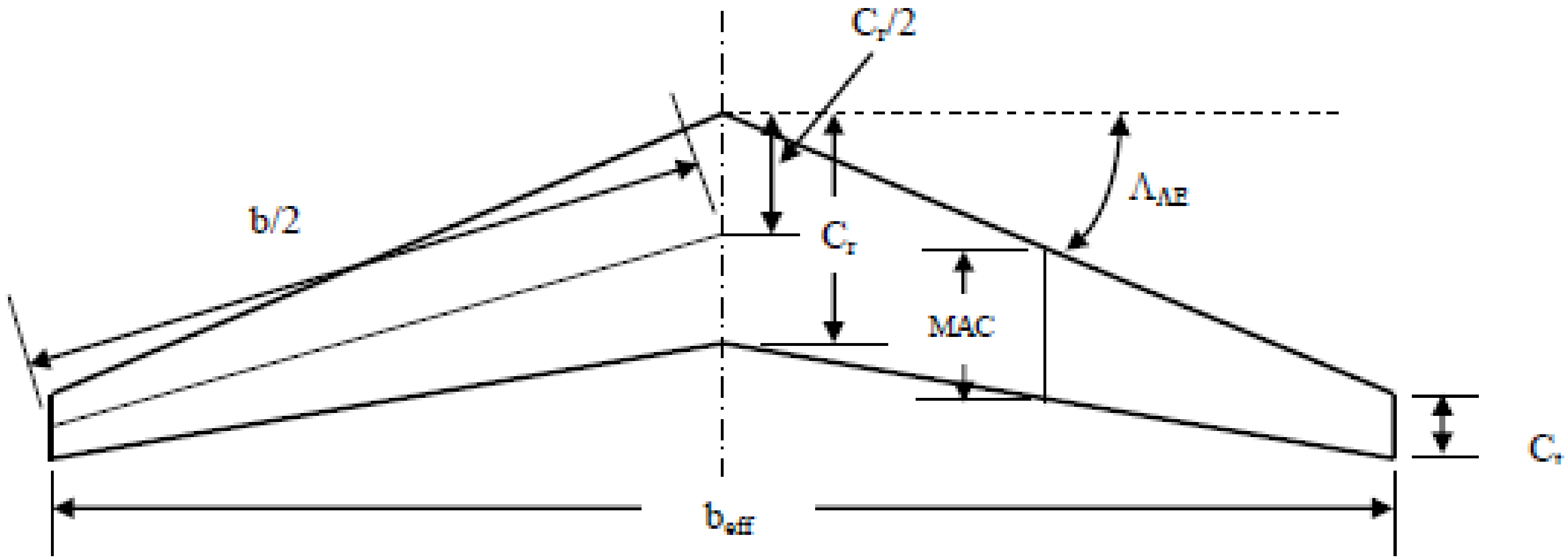
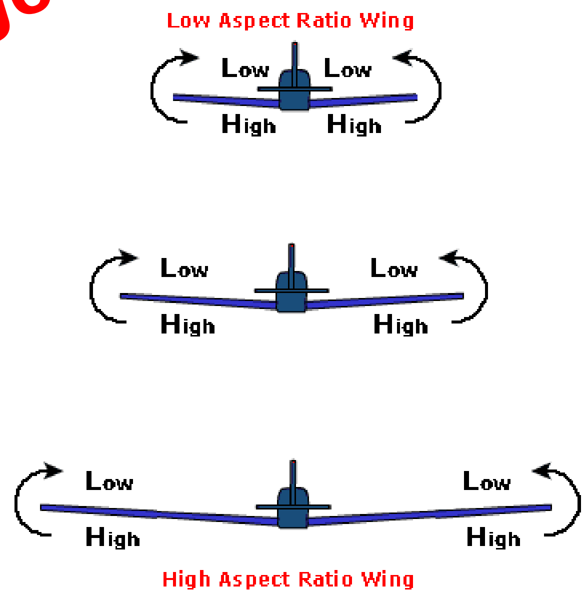


Figure 5.43. Effective wing span in a swept wing

Planform Effects and Induced Drag

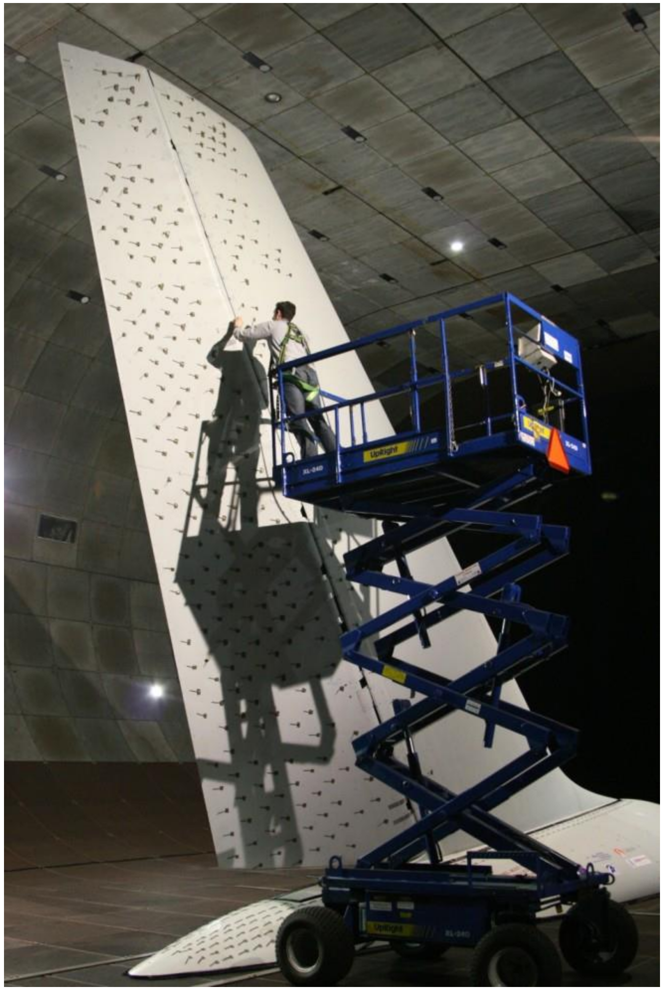


Skin Friction Drag

- The boundary layer air creates a stagnant layer of air molecules
- Drag is created when the slipstream comes in contact with this stagnant flow
- Varies directly with the airspeed

Hybrid Laminar Flow

- Begun in the 1980s (with the B-767) laminar air flow has been investigated to find ways to delay separation due to turbulence working forward from trailing edge
- Similar innovation now used on 787-9
- Tiny holes covering unpainted leading edge of 787-9's vertical tail used to control airflow over the surface
- Turbulent airflow is reduced using suction as air pulls turbulent layer through the small holes
- Technique used by NASA on F-16XL and recently by Airbus on A320 test aircraft in the late 1990s
- By ingesting the turbulent layer of air through the tiny holes, overall drag over the tail surface is reduced



Jet Aircraft Performance

Lecture 9

Thrust

- Relates to Newton's Second law (F = ma)
- Formula for Thrust $T = Q\,(V_2 - V_1)$

  Q = mass flow

  V^2 = exhaust gas exit velocity

  V_1 = inlet air velocity

Or, $Q = p\,AV$

So,

$T = p\,AV_1\,(V_2 - V_1)$

$$F = T = Q(V_2 - V_1)$$

where

T = thrust (lb)

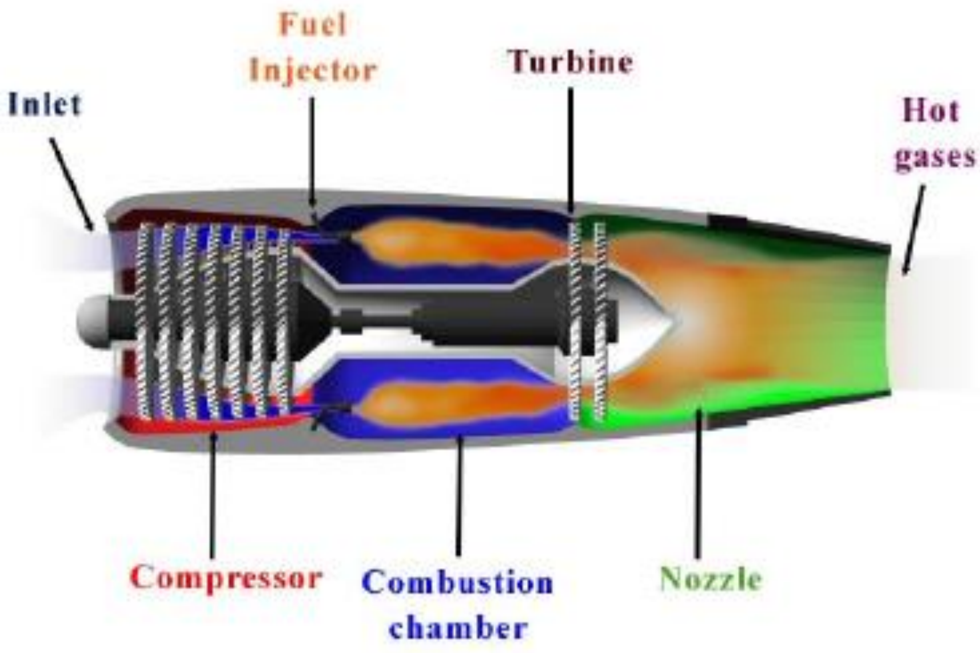
Q = mass airflow = p AV (Eq. 2.10) (slugs/sec)

V_1 = inlet (flight) velocity (fps)

V_2 = exit velocity (fps)

Turbojet

- Reduced expense of air travel and improved safety
- Faster speeds, longer range, higher payloads, lower mx
- 5 components – inlet, compressor, combustor, turbine, nozzle
- Can add an afterburner
- Heat from exhaust must be controlled (turbine blade cooling)

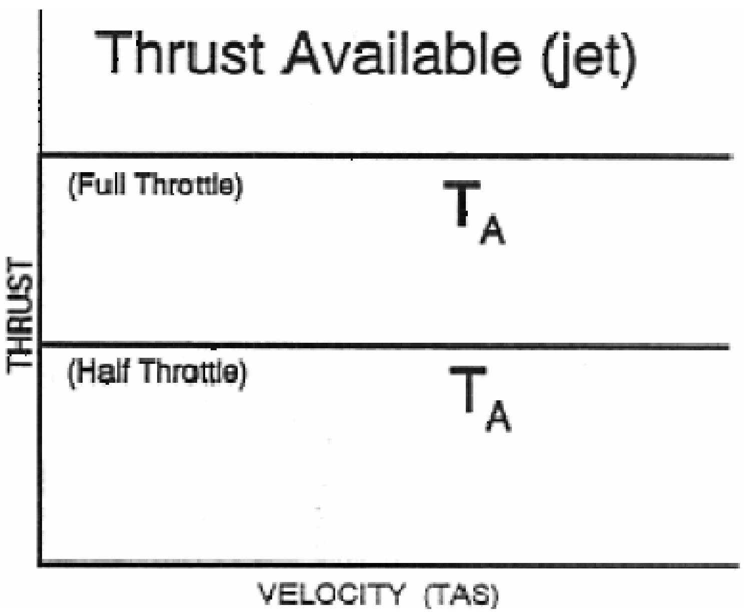


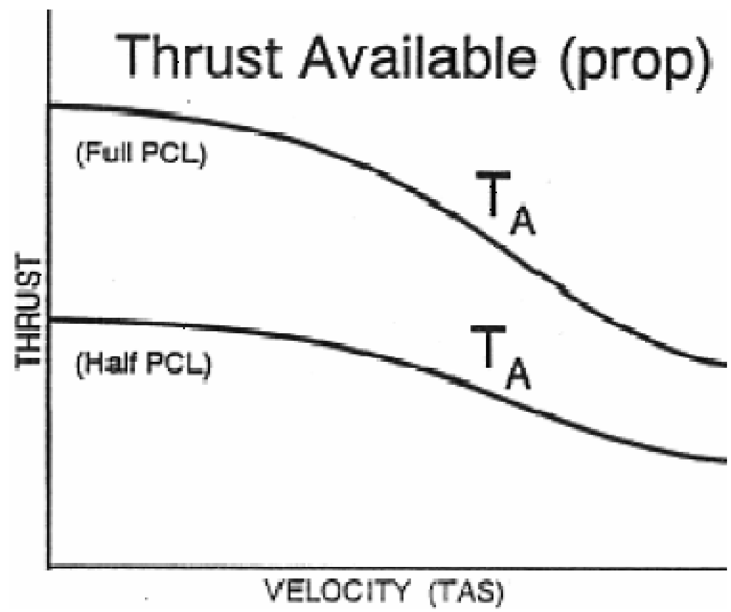
Thrust Available

T_A what is produced at a given throttle setting, velocity, and density

Turbojets have no decrease in T_A with V because ram-effect overcomes decreased acceleration

- So, T_A is a straight line
- As density increases, T_A increases

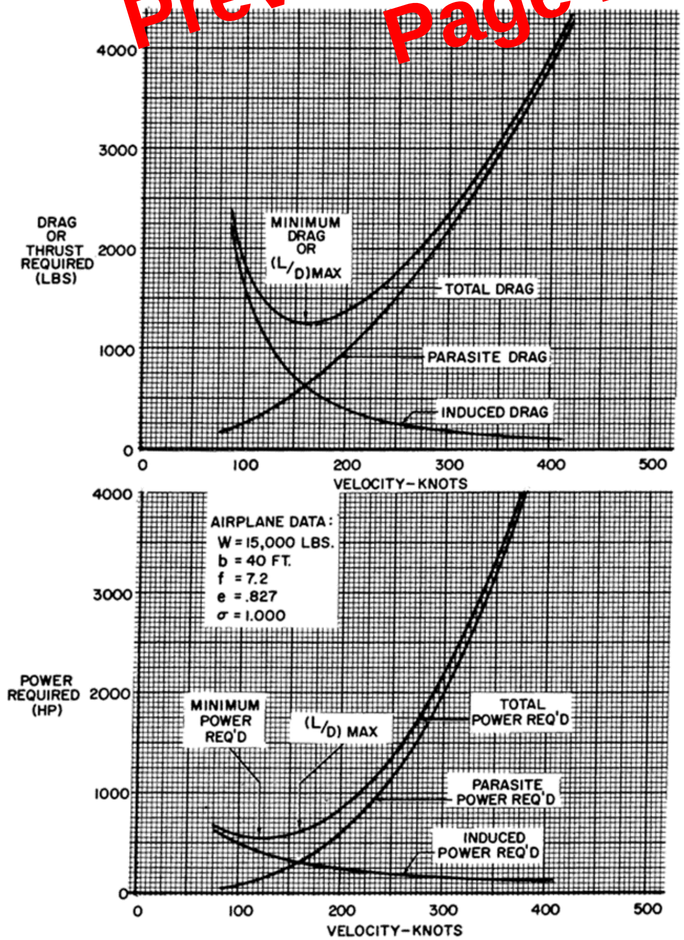


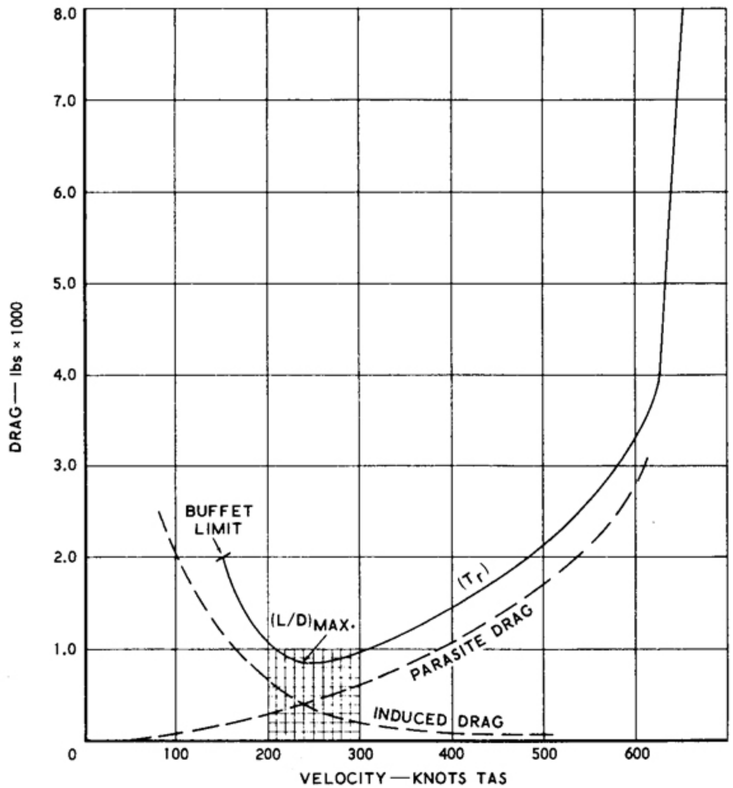


Drag or Thrust

Thrust required (top chart) for a turbojet

Note steep sides at both ends (more thrust to fly slow or fast in level flight)





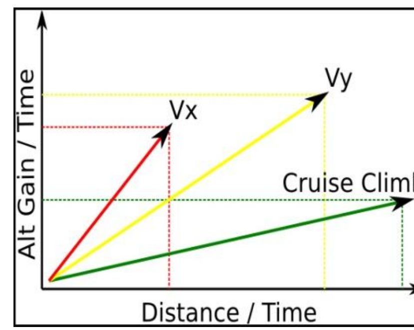
Rate of Climb

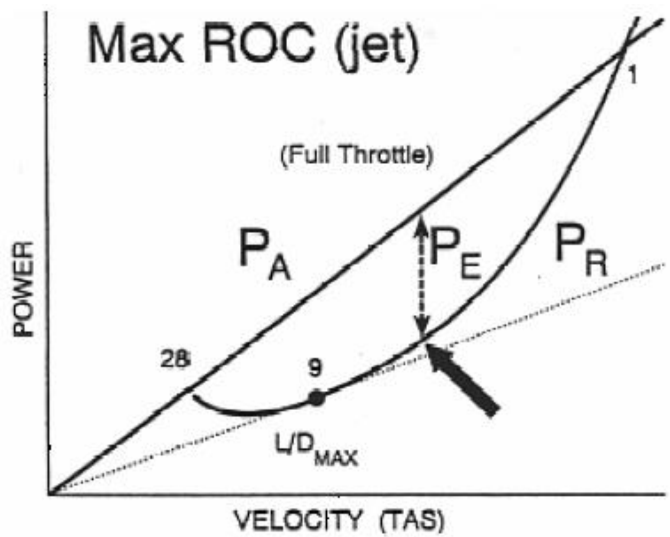
$$ROC = V \sin\gamma = \frac{VT_E}{W} = \frac{P_E}{W}$$

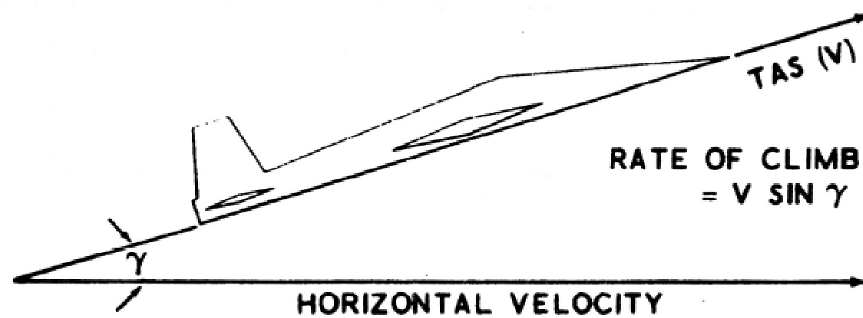
$$\begin{aligned} ROC &= V_k \sin\gamma && \text{(knots)} \\ &= V_k \frac{T_a - T_r}{W} && \text{(knots)} \\ &= 101.3 V_k \frac{T_a - T_r}{W} && \text{(fpm)} \end{aligned}$$

- ROC (V_Y)
- Depends on T_E

- Max rate occurs at V and AOA that produce Max T_E
- Max ROC for turbojet occurs at V greater than L/D_{MAX}, and AOA less than L/D_{MAX} AOA

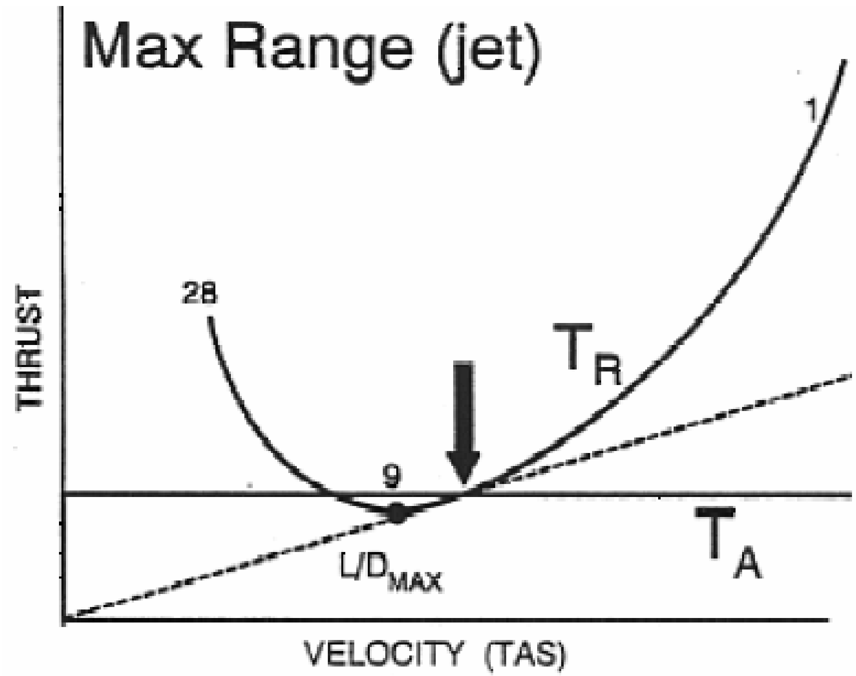






Maximum Range

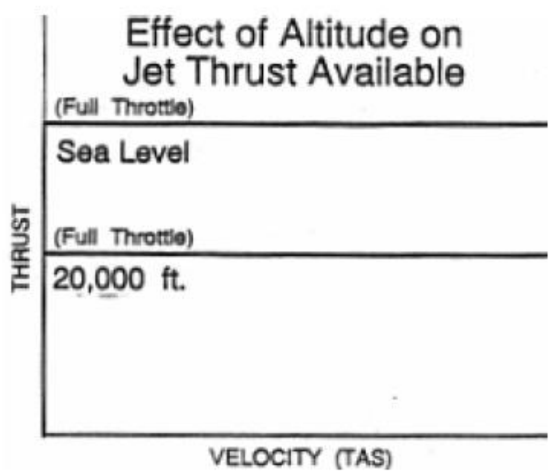
- Maximum distance traveled over the ground for a given amount of fuel
- Straight line shows constant ratio of fuel flow to V
- Min ratio to remain airborne is is line tangent to T_R
- Max range for turbojet = V >L/D_{MAX} and AOA <LD_{MAX}AOA

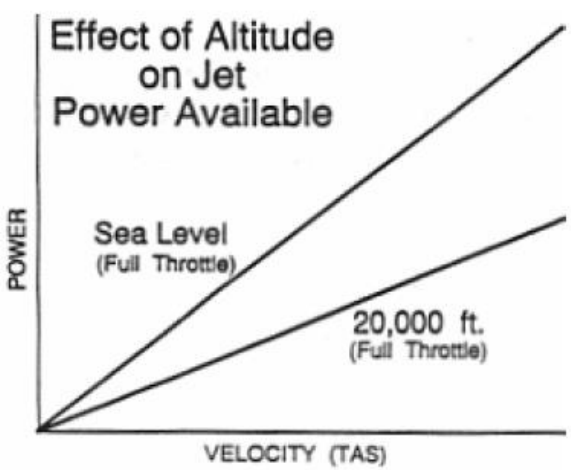


Altitude

- Maximum engine output decreases with a reduction in air density
- So, T_A will decrease at higher altitudes
- That means thrust excess will decrease

$$\overset{\downarrow}{T_E} = \overset{\downarrow}{T_A} - \overline{T_R}$$





Range

Effects of altitude on range

TA will decrease with alt

Drag =thrust in unaccelerated flight

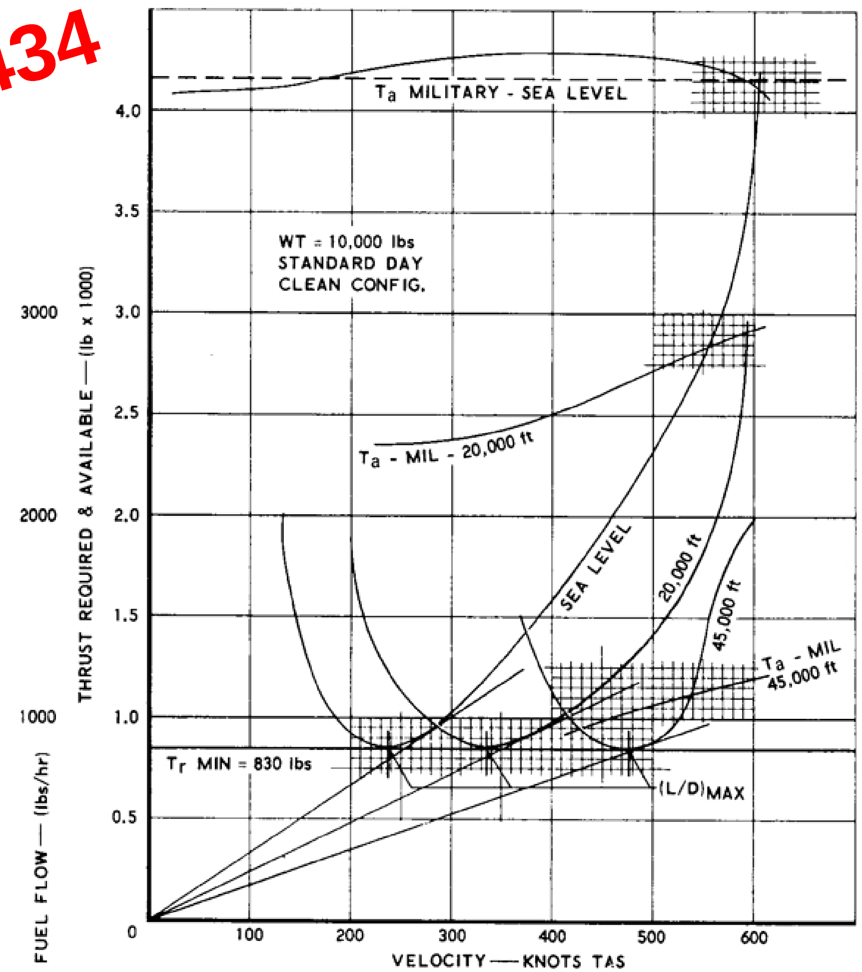
$D = C_D q S$

No change in S, but C_D and q change

C_D only changes with AOA
(if no high lift devices in use)

q changes with airspeed

At higher altitude, engines operate
cooler and increase RPM



PERFORMANCE FACTORS

TAKEOFF & LANDING

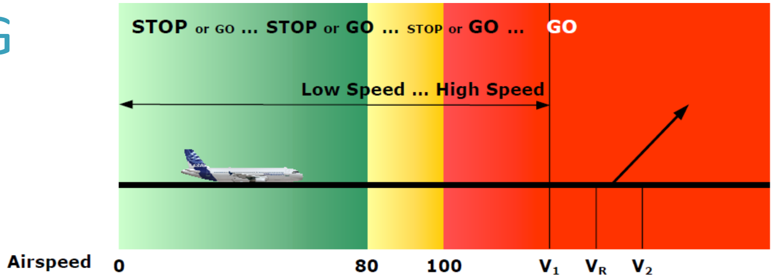
For a given altitude and RPM, the thrust from a propeller-driven airplane *decreases* as velocity increases during the takeoff roll.

Takeoff

- Takeoff speeds are a key safety element for takeoff, and enable pilot situational awareness and decision-making
- Use of incorrect takeoff speeds can lead to tail strikes, high-speed rejected takeoffs or initial climb with degraded performance
- During the takeoff roll, it is of utmost importance to know the minimum speed at which the aircraft will remain controllable, in the event of an engine failure on ground
- This is because, if the takeoff is continued, only the rudder will be able to counteract the yaw moment generated by asymmetric engine(s) thrust

- By regulation, minimum speed at which an aircraft is defined to be "controllable" (lateral excursion lower than 30 feet) after an engine failure on ground, is referred to as VMCG (Velocity of Minimum Control on Ground)

- VMCG mainly depends on:
  - Engine(s) thrust
  - Pressure altitude
- If failure occurs before V1: Decision Speed
  - V1 is the maximum speed at which a rejected takeoff can be initiated, in the event of an emergency
  - V1 is also the minimum speed at which a pilot can continue a takeoff after an engine failure
- If an engine failure is detected after V1, the takeoff must be continued
- This implies that the aircraft must be controllable on ground
- Therefore, V1 is always greater than VMCG



VMCA (Velocity of Minimum Control in the Air)

- The rudder is used to compensate for the yaw moment caused by thrust asymmetry
- There is a minimum speed at which full rudder will be necessary, in order to fly a constant heading with level wings
- To reduce sideslip, this speed can be reduced even more, if the aircraft is banked on live engine's side
- The lower the speed, greater the necessary bank angle
- The speed that corresponds to a 5-degree bank angle is defined, by regulations, as the minimum control speed and is referred to as VMCA (Velocity of Minimum Control in the Air)

Takeoff Safety Speed

- V2 is the minimum speed to be maintained up to acceleration altitude, if an engine failure after V1
- Flight at V2 ensures minimum required climb gradient is achieved, and aircraft is controllable
- V2 speed is always greater than VMCA, and facilitates control of the aircraft in flight
- In an all-engines operative takeoff, V2+10 provides a better climb performance than V2
- If one engine is lost before reaching V2, initial climb is flown at V2
- If thrust is lost at speed between V2 and V2+10, current speed is maintained to ensure most efficient climb speed
- Not necessary to increase pitch, in order to reduce speed to V2, when higher speed already has been reached

PERFORMANCE FACTORS

TAKEOFF & LANDING

HYDROPLANING SPEED

$$\sqrt{\mathbf{TP\ (9)}}$$

Power

$$P_R = \frac{T_R \cdot V}{325}$$

Power is the rate of doing work

Work is a force x a distance

P_R – what is required to produce T_R

$P_R = T_R \times V$

When expressed in knots, product is divided by 325 to give power in units of horsepower

Can be expressed as THP or SHP, but usually as P

Usable horsepower is in THP

To find L/D_{MAX} draw line tangent to bottom of curve

Note L/D_{MAX} not at bottom

Min P_R is left of L/D_{MAX}

Thrust bucket

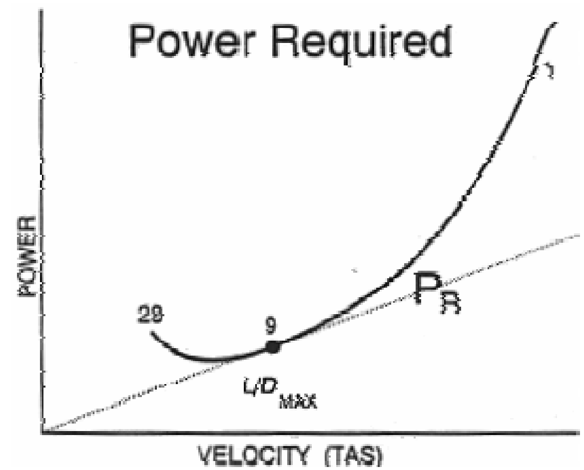


Figure 1-6-3 Power Required

Power

P_R – what is required to produce T_R

$P_R = T_R \times V$

$$\text{Power} = \frac{\text{work}}{\text{time}} = \frac{\text{force} \times \text{distance}}{\text{time}} = \text{force} \times \text{speed} \quad \text{(ft-lb/sec)}$$

James Watt defined the term *horsepower* (HP) as 550 ft-lb/sec:

$$\text{Horsepower} = \frac{\text{Force} \times \text{Speed}}{550}$$

Speed is Velocity in Feet-Per-Second (FPS)

If the speed is measured in knots, V_k, and the force is the *thrust*, T, of a jet engine, then

$$\text{HP} = \frac{\text{Thrust} \times V_k}{325} = \frac{TV_k}{325}$$

$$P_R = \frac{T_R \cdot V}{325}$$

$$P_r = \frac{DV_k}{325}$$

Gyroscopic precession

- A left-turning tendency during takeoff in taildragger aircraft only.

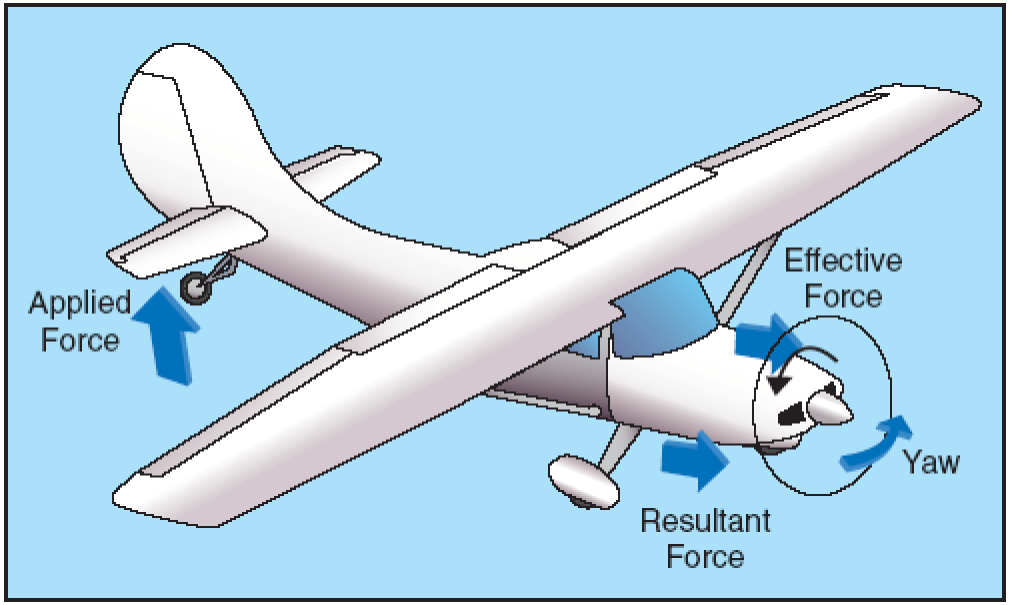
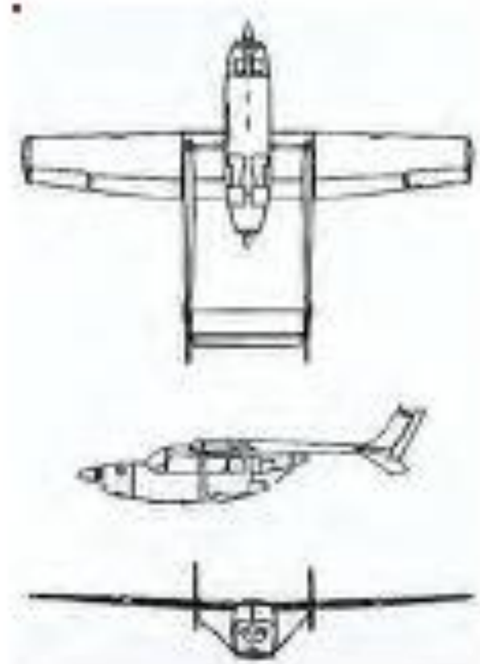


Figure 3-33. Raising tail produces gyroscopic precession.

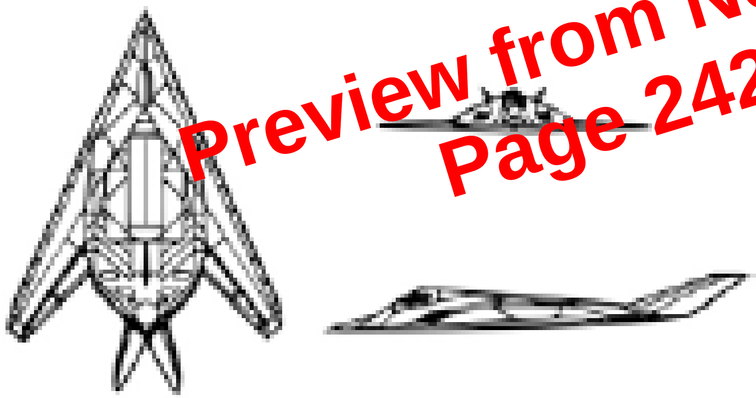
General Aviation Aircraft

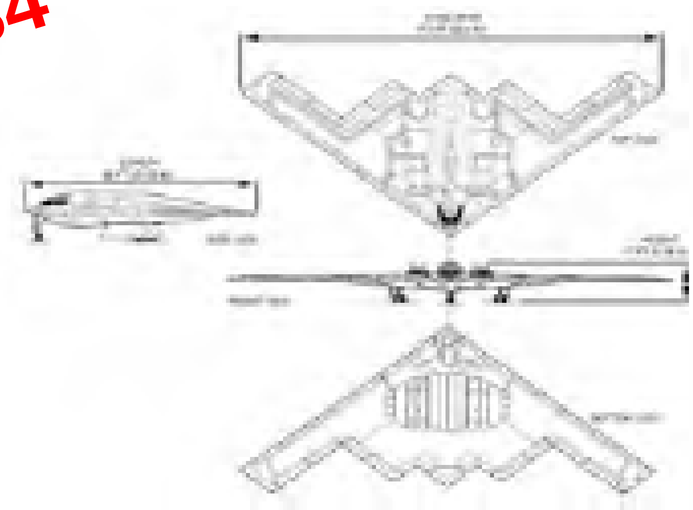
Low cost, safety, comfort, ease of handling

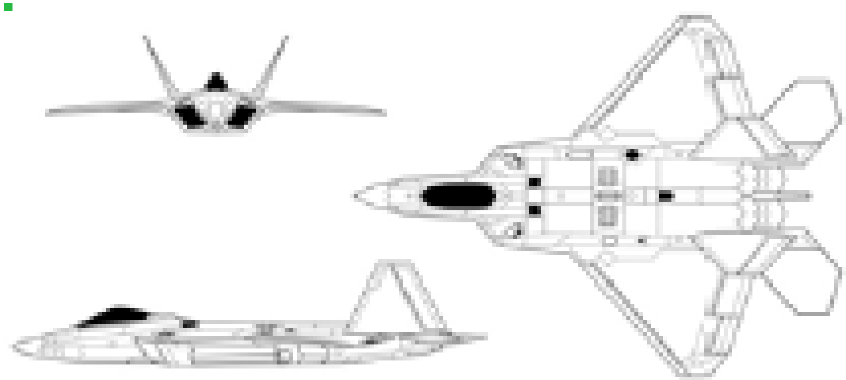


Approaches to Stealth

- Low radar cross-section







- Open-loop instability
- Need for closed-loop control

Stability

- Two primary categories of stability

Static

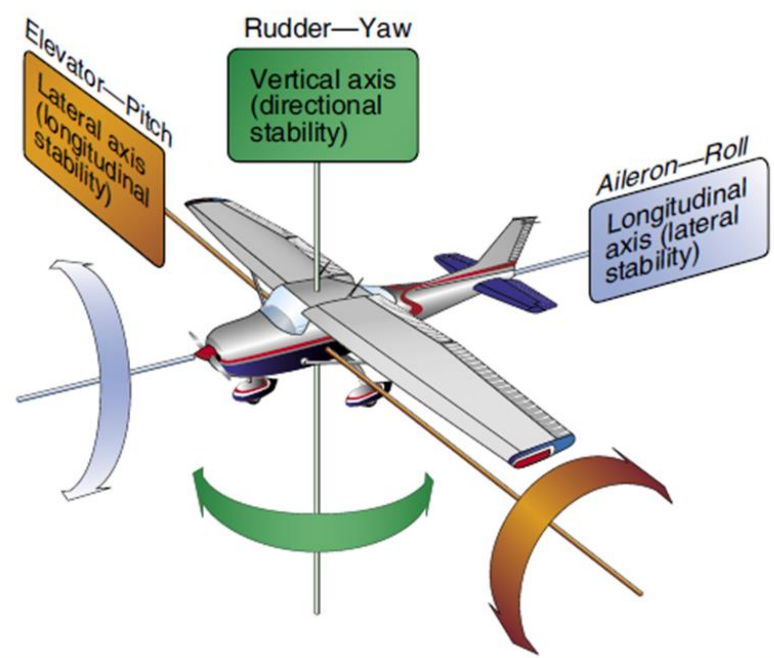
- initial tendencies of aircraft after equilibrium disturbed (trimmed condition)

Dynamic

- overall tendency the aircraft displays after equilibrium is disturbed, often after a series of damped out oscillations

Axes of Flight

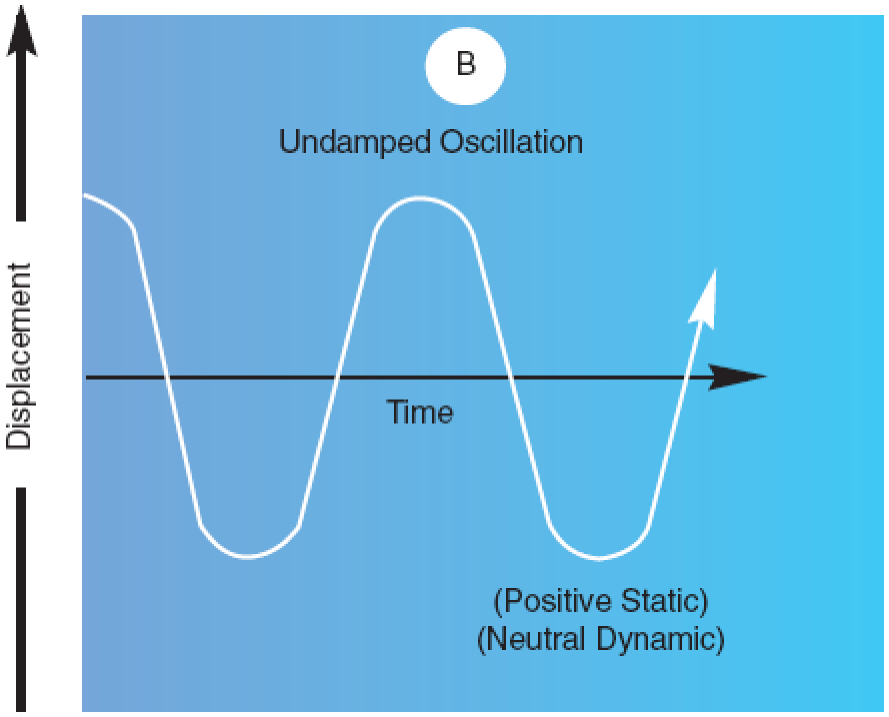
Figure 3-9. Axes of an airplane.



- Roll > ailerons (wings)
- Pitch > elevators (nose or tail)
- Yaw > rudder (tail)
- Note: From naval terms

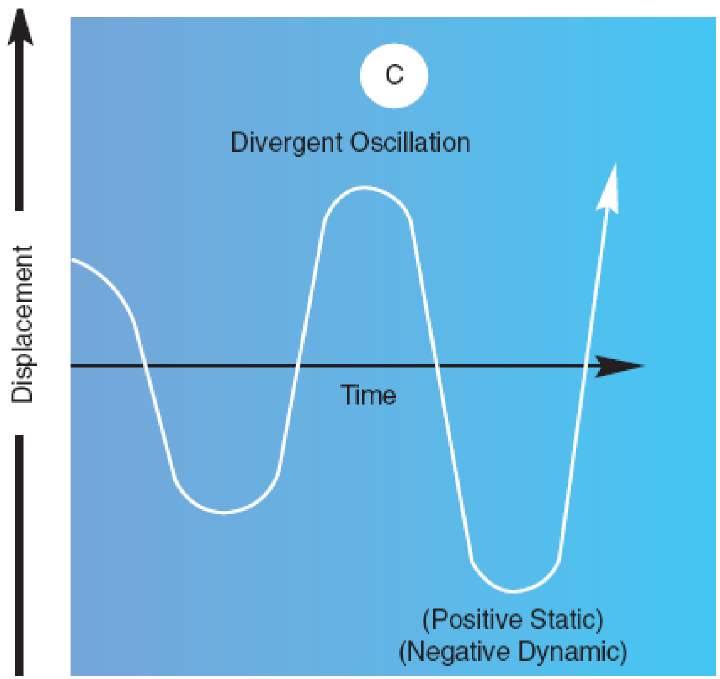
Dynamic Stability

- Neutral dynamic stability
  - Persistent (phugoid) oscillations



Dynamic Stability

- Negative dynamic stability
  - Increasing (divergent) oscillations
  - Never returns to equilibrium
  - Avoid at all costs



Straight Wings

- During sideslip, advancing wing (straight wing planform) has momentary airflow V increase which increases D_P and pulls it back into equilibrium
- Retreating wing has less V and D_P bringing nose back into RW
- Straight wings have a small positive effect on directional static stability
- *Straight wing aircraft are more sensitive to AoA changes (like wind gusts)*

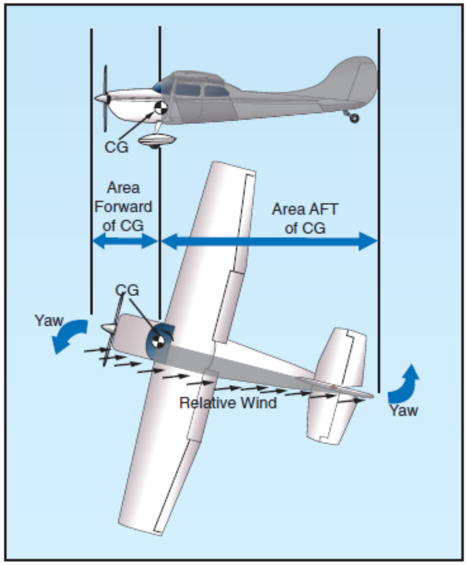


Figure 3-19. Fuselage and fin for vertical stability.

Dutch Roll

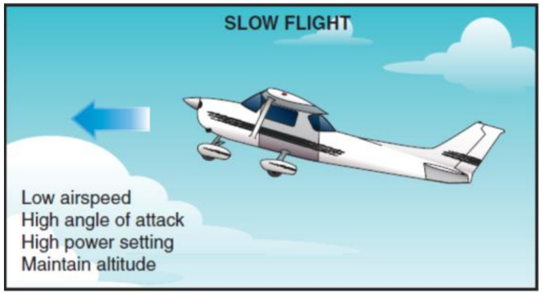
- When a sideslip excursion occurs
  - Dihedral effect causes roll opposite the sideslip
  - Then static directional stability returns aircraft back into relative wind
  - Depending on N_r and L_P , a/c will oscillate in yaw and roll
  - If dynamically stable, a/c will return to steady state flight
- If dihedral effect is strong, oscillations will be more roll than yaw
- If dihedral is weak, oscillations will be mostly yaw
- Typical airliner with swept wings will exhibit angle of bank oscillations twice those in sideslip
- Adverse and proverse yaw can initiate Dutch roll

Slow Flight, Stalls and Spins

Lecture 14

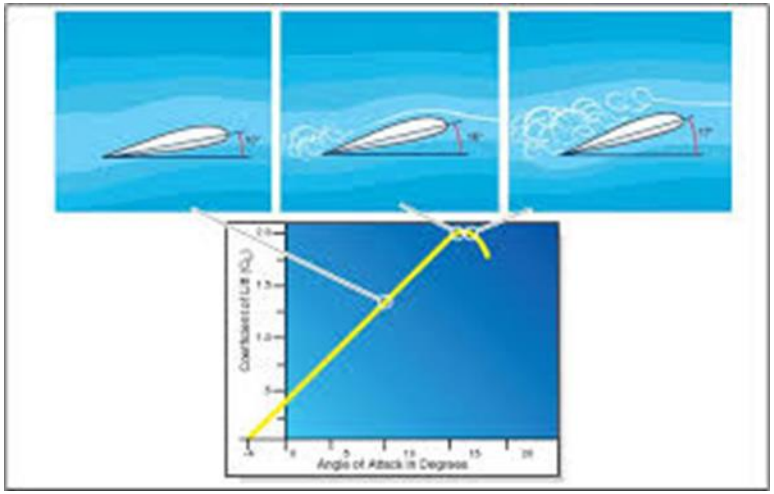
Slow Flight

- Generally considered as less than cruise speed
- Two primary elements:
  - Establishing, maintaining, and maneuvering a/c at airspeeds in configurations like TO, climb, descent, approaches, LND, and go around
  - Maneuvering at slowest airspeed capable of maintaining controlled flight without stall indications (3 to 5 kts)
- Primarily for training, but used in commercial applications (survey, cameras, parachute drops)
- Involves slowing without loss of altitude or heading
- Includes configuration changes (flaps, gear, bay doors)



Minimum Controllable Airspeed

- Practiced in instrument and visual conditions
- Speed at which any further increase in AoA, load factor, or reduction in power will cause immediate stall
- Typically done in stages (slow, maintain alt/hdg, flaps, gear, flaps, climb or descend, stabilize, recovery)
  Note: retract flaps too quickly and lose alt or stall



Stall

- Boundary layer separation
- Significant decrease in lift

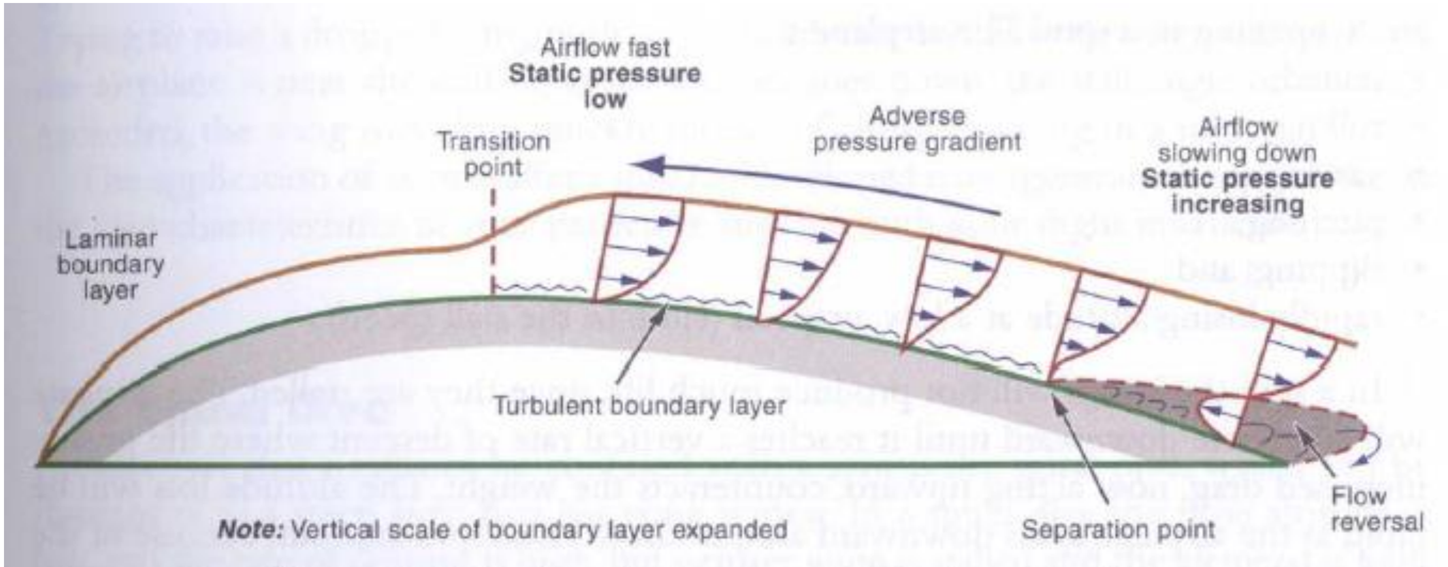
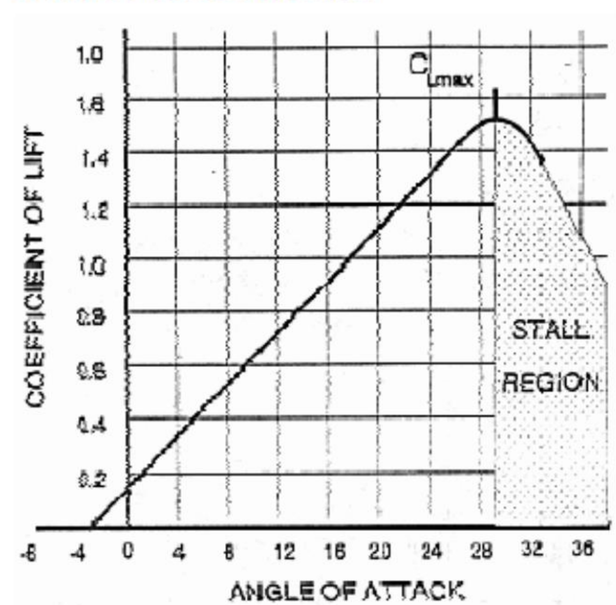


Figure 3-55 The boundary layer over the wing's upper surface.

Stall AoA

- A stall is a condition of flight in which an increase in AoA results in a decrease in C_L
- Note that C_L increases linearly over a large range of AoA, then reaches a peak and begins to decrease
- The highest value of C_L is referred to as C_{Lmax}, and any increase in AoA beyond C_{Lmax} AoA produces a decrease in CL
- Therefore, C_{Lmax} AoA is known as the stalling angle of attack or critical angle of attack, and the region beyond C_{Lmax} AoA is the stall region

STALL INDICATIONS



Stall AoA

- Turning flight
  - VS is higher in a level turn
  - Centrifugal force is added to a/c weight requiring additional lift
  - VS is higher in a level turn than in straight-and-level flight
  - This is because centrifugal force is added to the a/c weight, and the wing must produce sufficient additional lift to counterbalance the load imposed by combination of centrifugal force and weight
  - In a turn, necessary additional lift is acquired by applying back pressure to the elevator control which increases the wing's AoA and results in increased lift
  - The AoA must increase as the bank angle increases to counteract the increasing load caused by centrifugal force
  - If at any time during a turn the AoA becomes excessive, the a/c will stall

Geometric Twist

- Is the twist of an airfoil having different geometric angles of attack at different spanwise locations
- Root has greater angle of incidence than tip
- Root operates at an aerodynamically AoA
- Is accomplished by designing different values of C_L maximum along span the wing

Stalls

- Stalls cannot be eliminated, but can be made more predictable by having the wing stall gradually
- Since most airplanes do not have rectangular wings, they tend to stall with little or no warning
- Wing tailoring techniques are used to create a root to tip stall progression and give the pilot some stall warning while ensuring that the ailerons remain effective up to a complete stall
- Trailing edge flaps decrease stalling angles of attack in their vicinity, causing initial stall in the flap area
- Boundary layer control devices and vortex generators are used to delay BL air separation and to inhibit stall near wing tips
- Propeller a/c may have a tip stall tendency during power-on stalls due to the increased airflow over wing root

Aerodynamic Twist

- Spanwise flow on a swept wing is not accelerated over the wing and does not contribute to the production of lift
  - Instead, it induces a strong tip stall tendency
  - Stall fences redirect airflow along the chord, delaying tip stall and enabling wing higher AoA without stalling

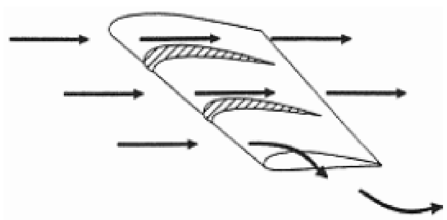


Figure 1-4-20 Stall Fences

  - A sharply angled piece of metal (stall strip) is mounted on the leading edge of the root section to induce a stall at the wing root
  - Since subsonic airflow cannot flow easily around sharp corners, it separates the boundary layer at higher angles of attack, ensuring that the root section stalls first

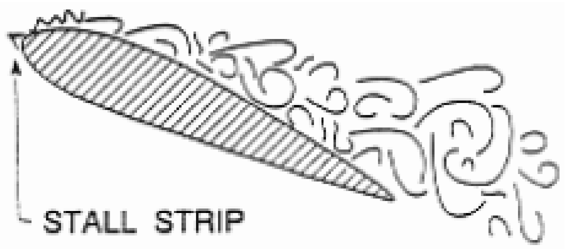


Figure 1-4-21 Stall Strip

Stall Recovery

- To produce required lift at slow speeds, must fly at high AoA
- Flying slow at high AoA is a critical phase of flight, so pilots practice recovering from several types of stalls
- Steps in a stall recovery involve simultaneously adding power, relaxing back stick pressure and rolling wings level ("max, relax, level")
  - Add power to increase airspeed, break descent (especially at low altitudes) and restore a V greater than V_S
  - Decrease the AoA to recover from a stalled condition
  - Initial reaction is to pull nose up, however, exact opposite must be done
  - Control must be moved forward to decrease AoA and allow wing to provide sufficient lift to fly once again
  - By lowering nose, AoA is decreased and boundary layer separation point moves back toward trailing edge, restoring lift
  - Pilot rolls out of bank to wings level to decrease stall velocity and use all available lift to break any further descent

Spin

- Early in aviation, a spin usually ended in a fatality (airmail)
- Once understood, pilots have practiced recovering from spins
- The spin itself, however, has no practical value as a maneuver
- There are three reasons for teaching spins
  - every aircraft that is capable of stalling has the potential for entering a spin (in high performance aircraft, many maneuvers are flown near the stall region)
  - spin training builds confidence in ability to handle an aircraft should it inadvertently enter a spin
  - spin training improves a pilot's ability to remain oriented and still make appropriate control inputs
- Aircraft have different spin characteristics and recovery techniques
- Therefore, the pilot must know the flight manual procedures for spin prevention and recovery for aircraft they fly

Aggravated Stall

- A spin is an aggravated stall that results in autorotation
  - Autorotation is a combination of roll and yaw that propagates itself and progressively gets worse due to asymmetrically stalled wings
- For an aircraft to spin, it must reach stalled AoA and have excessive yaw
- If an aircraft is not stalled, it will not spin
- If either the stall or yaw is removed, the aircraft will not continue to spin
  - A yawing moment can be induced with the rudder, by adverse yaw, gust wing loading, etc.
  - If a stalled condition is maintained long enough, sufficient yaw to enter a spin could eventually be introduced
- Every aircraft exhibits different spin characteristics, but they all have stall and yaw about the spin axis
- Remember that while both wings are stalled, they do not lose all their lift, nor are they equally stalled

Region of Normal Command

- Velocities above L/D_{MAX} are referred to the region of normal command, characterized by airspeed stability
- Assume a/c is in equilibrium, decrease in airspeed results in T_E to use to accelerate back to original airspeed
- In the region of normal command, V and throttle setting for level flight are directly related
- To fly in equilibrium at a faster airspeed, more T_A is needed than at a slower airspeed (and v/v)

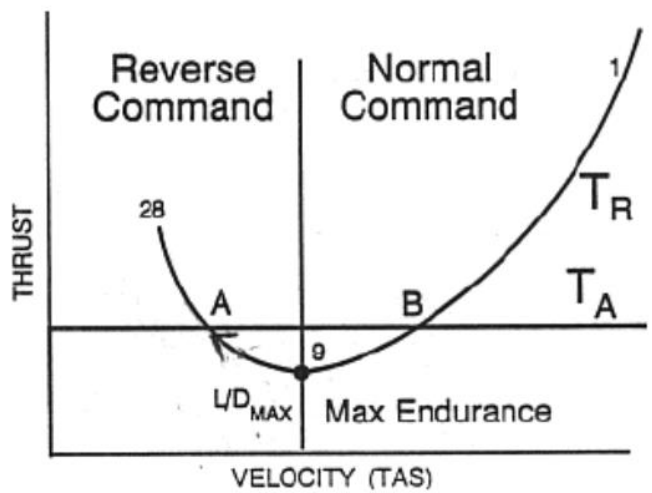


Figure 1-7-21 Turbojet Reverse Command

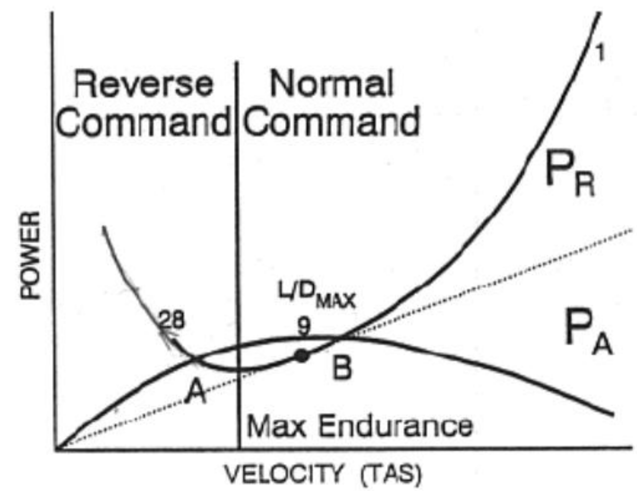


Figure 1-7-22 Turboprop Reverse Command

Design Limits

- Structural limits of a/c are due to metal skeleton or airframe
  - When wing produces lift, it bends upward and deforms if lift too great
  - Airframe components, like wings, determine max load a/c can withstand
- The two greatest loads on an a/c are lift and weight
  - Weight does not vary much by the moment, so lift causes max load to be exceeded
  - Difficult to measure amount of lift, but easy to measure acceleration
- Since acceleration is proportional to force (Newton's 2nd Law), if weight of a/c is known, lift can be determined by monitoring a/c acceleration
- Since load factor is a ratio of a/c lift to wt, and mass being accelerated by lift and wt is the same mass, load factor is acceleration due to lift expressed as a multiple of earth's acceleration, as measured by an accelerometer
- Design limits include the limit load factor, ultimate load factor, redline airspeed and maneuvering parameters

Ultimate Load Factor

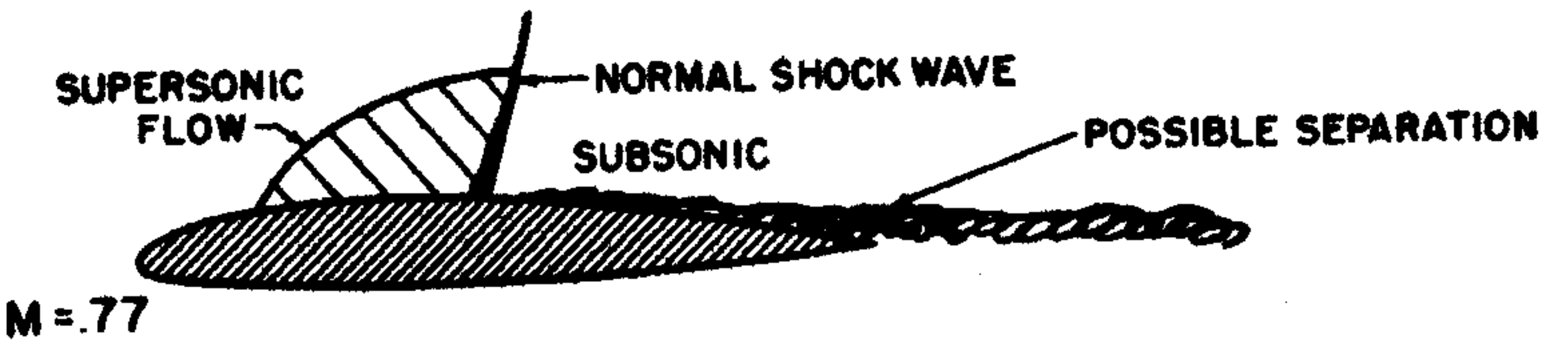
- Is the maximum load factor a/c can withstand without structural failure
- Will be some permanent deformation at the ultimate load factor, but no actual failure of the major load-carrying components should occur
- If exceed ultimate load factor, structural failure is imminent (something major on a/c will break)
- Ultimate load factor should be avoided since most a/c are difficult to fly after wings tear off
- Ultimate load factor is 150% of limit load factor

High Speed Flight

- Subsonic (Mach ~0.7 or less)
  - All airflow around wing aircraft is subsonic
- Transonic (Mach ~0.7 to ~1.3)
  - Airflow around aircraft is partially subsonic and partially supersonic
- Supersonic (Mach ~1.3 to 5.0)
  - All airflow around aircraft is supersonic
- Hypersonic (above Mach 5.0)
  - Aircraft speeds above Mach 5.0

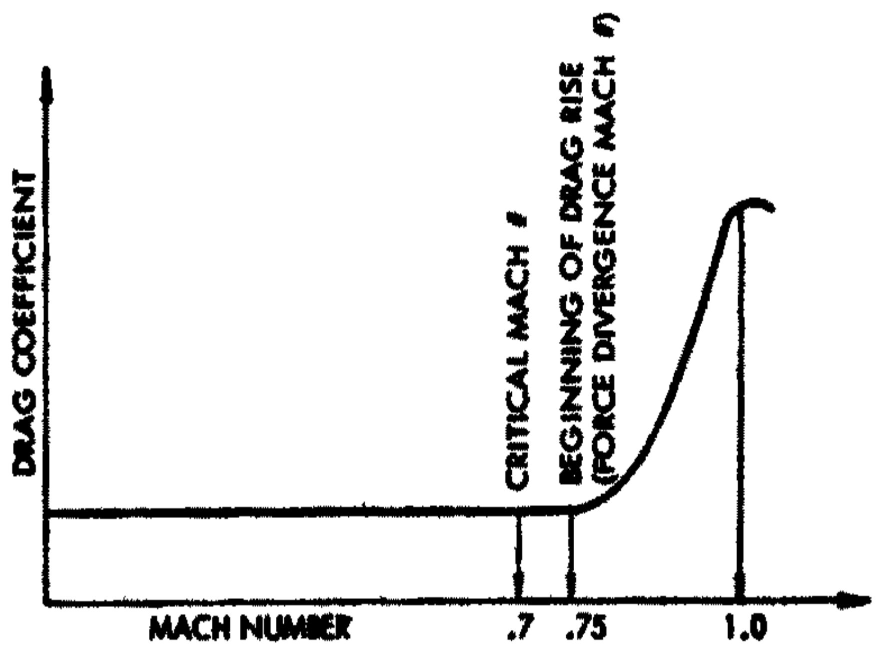
High Speed Buffet

- Increased pressure caused by shock wave above the wing creates same effect as an adverse pressure gradient
  - Causes airflow to <u>separate</u>
  - Results in <u>high speed stall</u>
  - May experience buzz and possible <u>control loss</u>



Force Divergence

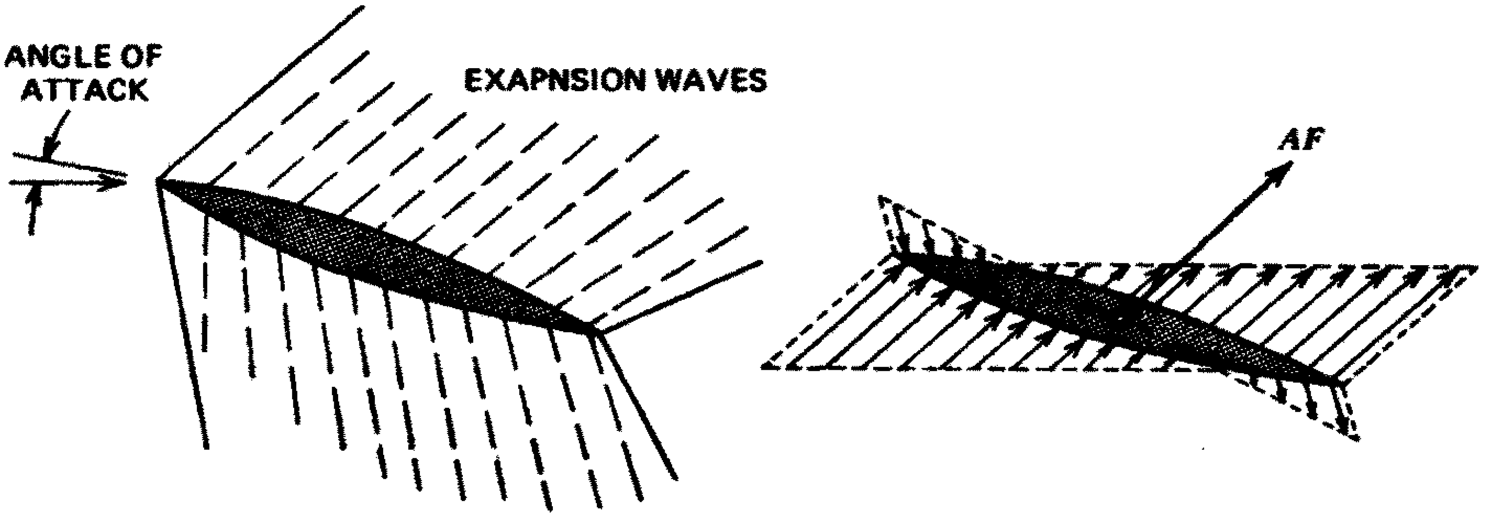
- Mach number which produces a sharp change in drag coefficient, is termed “force divergence ” and usually exceeds M_{crit} by 5 to 10%
- Effects of force divergence Mach number include increased C_L and C_D for a given C_L
- Use of sweepback will “soften” force divergence



Supercritical Airfoils

(Circular Arc or Bi-convex)

- **Allows normal shock wave where upper surface pressure gradient is favorable**
- **Is designed with less curvature on upper surface **
- Avoids some of the poor low speed problems associated with the double-wedge airfoil

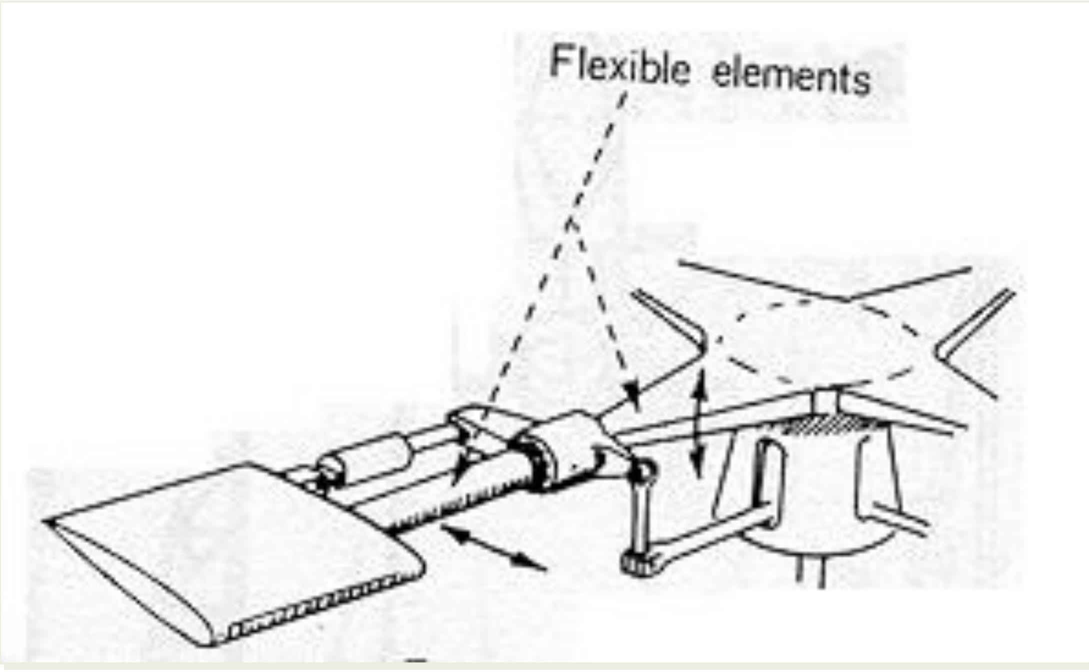


Rotor Systems

- Semi-rigid (Bell-205)
- Articulated (AS-330)
- Intermeshing (Kaman K-Max)
- Tandem (Boeing 46)
- Coaxial (Kamov Ka-50)
- Hingeless (BK-117)
- Bearingless (EC-145)
- Transverse (AW 609)
- Hybrid (ABH-X3)

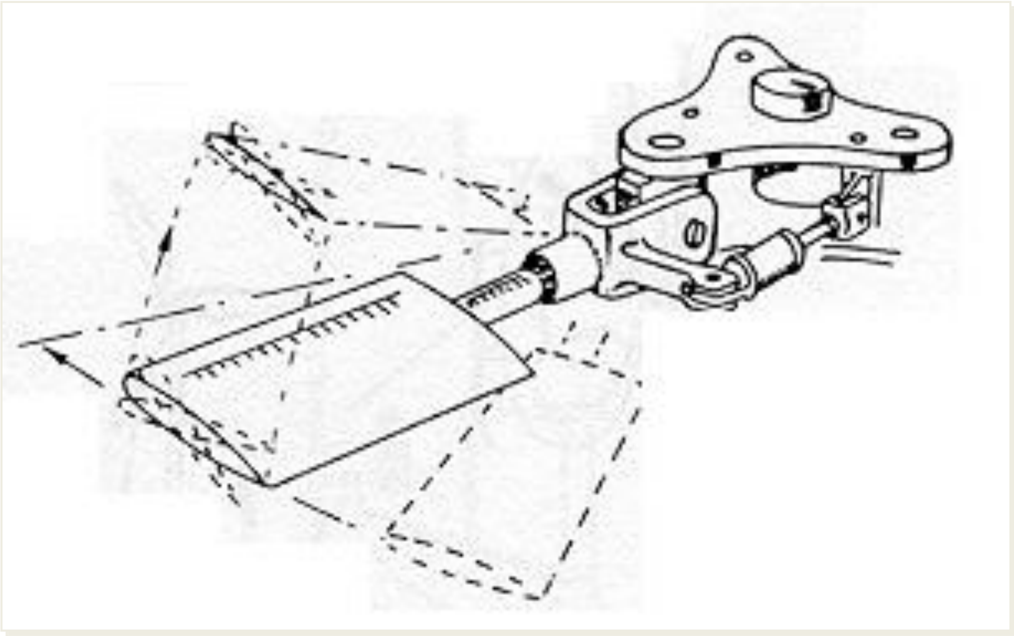
Semi-Rigid Rotor System

- Normally two bladed systems
- Teetering "see-saw" or underslung
- Blades move in two directions
  - Feather
  - Flap
- Bell UH-1 Huey



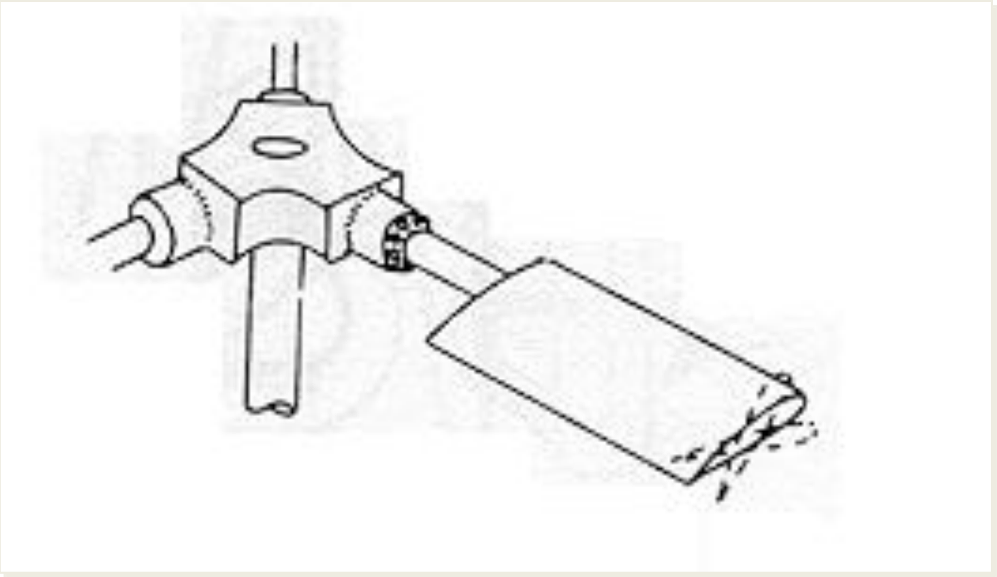
Fully Articulated Rotor System

- **3 or more blades that lead, lag, and flap**
- Blades travel independently of each other through full range of motion
- Anti-flap bushings
- Dampers
- Sikorsky H-60



Rigid Rotor System

- Mechanically simple, structurally complex
- Smaller, simpler helicopters
- Minimal blade movement
  - Blades absorb most movement
  - Feather only (pitch)
- MBB Bo 105



Blade Twist

- **Helicopter blades are designed with a twist in order to prevent uneven lift distribution**
- Twist offsets differential lift caused by blade speed
- Twisted blades generate more lift near the root and less lift at the tip than untwisted blades