Aerodynamics

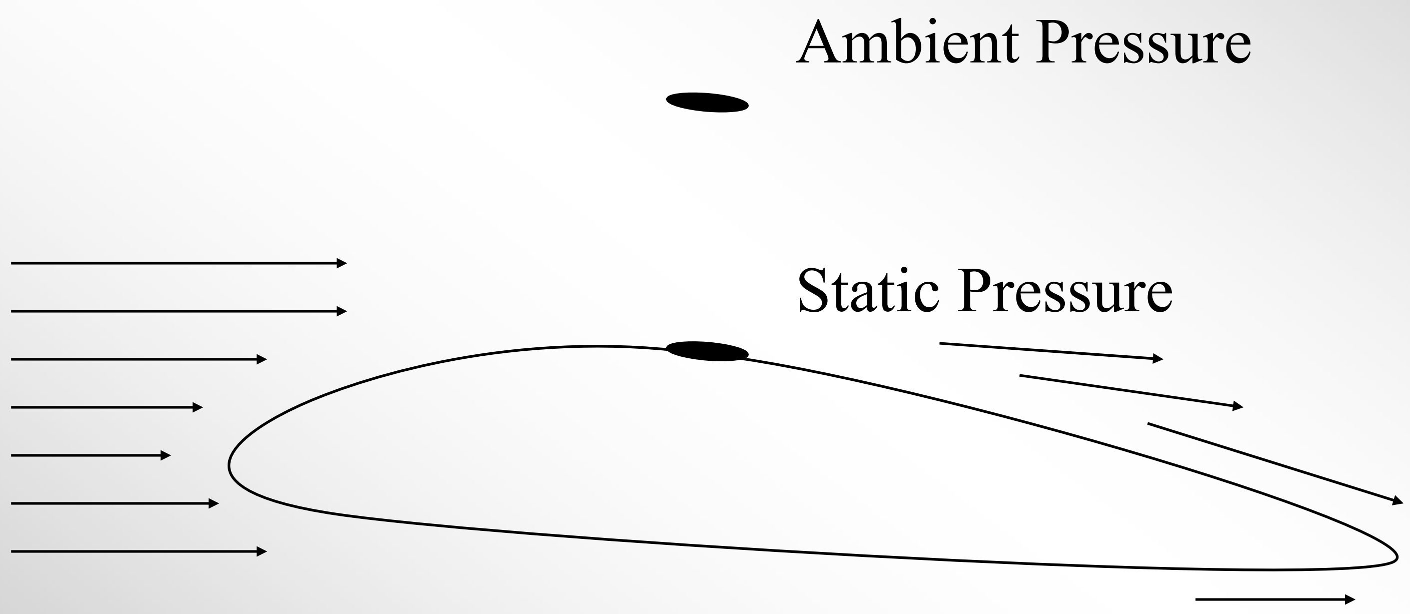
SYST 460/560

George Mason University
Fall 2008

CENTER FOR AIR TRANSPORTATION SYSTEMS RESEARCH

GEORGE MASON UNIVERSITY

Ambient & Static Pressure



Ambient and Static Pressure

- Two pressures:
  - Static
    - Pressure on body in flow
    - Pressure drops due to local speed of flow
  - Ambient
    - Pressure in neighborhood of moving body, but far enough away not to be affected by flow
- Ambient Pressure > Static Pressure
- Altitude and Airspeed measured by Static Pressure (through static pressure port)
  - Correction is necessary to determine Ambient Pressure

Ambient and Static Pressure

- Ambient pressure = δ
  - Pressure Altitude < 36,089 ft

    δ = (1-6.88 X 10-6 Pressure Altitude)$^{5.26}$
  - Pressure Altitude > 36,089 ft

    δ = (0.223360 e $^{[(36089 - \text{Pressure Altitude})/20805.7]}$

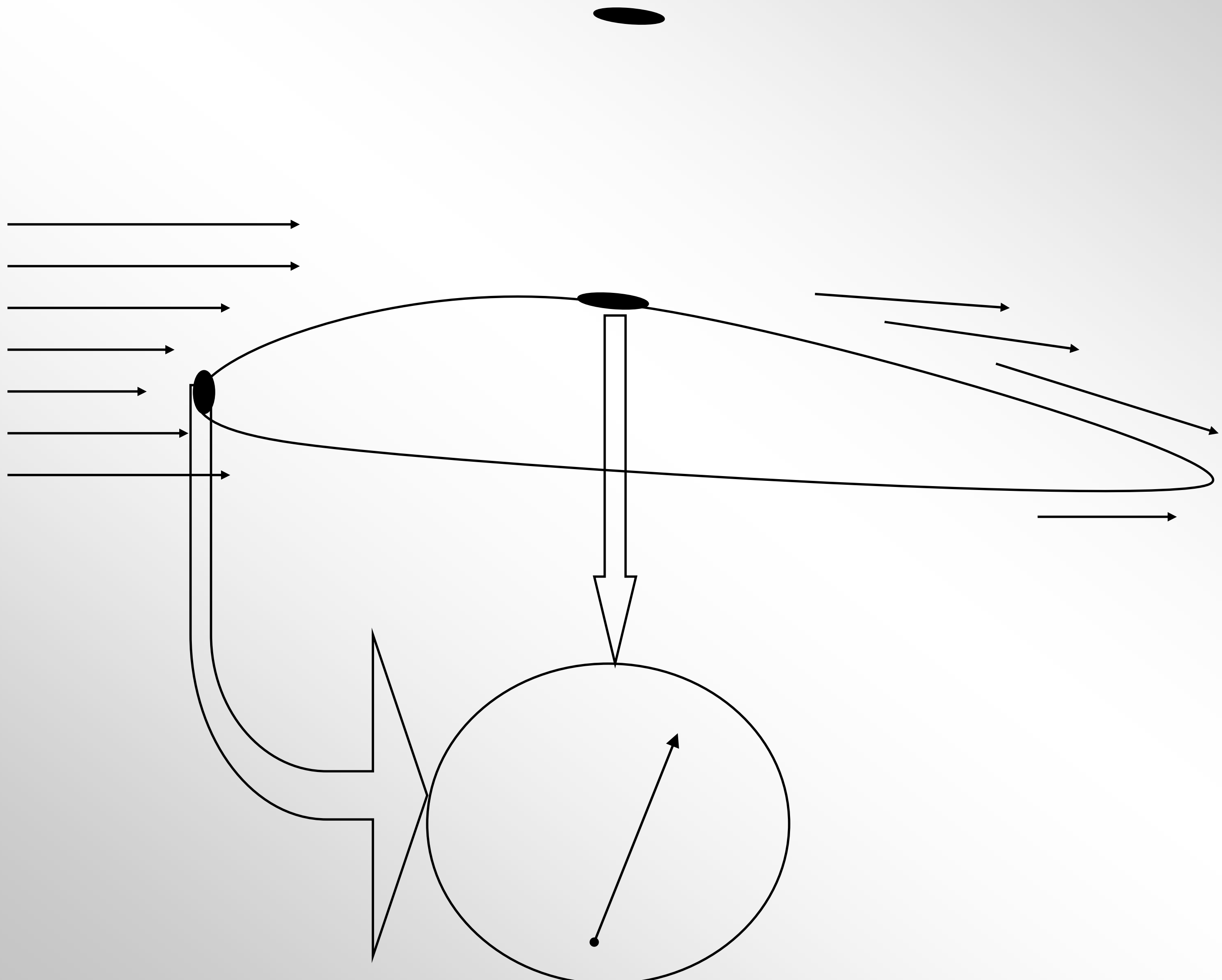
Altitude

- Altitude Measurements (4):
  1. Pressure Altitude
     - Pressure differential with respect to Pressure at Sea Level
  2. Geometric Altitude
     - Physical distance between aircraft and reference (e.g. Sea Level)
  3. Density Altitude
     - Difference in density with International Standard Atmosphere (ISA) temperature
  4. Geopotential Altitude
     - Distance between Center of Earth and parallel surfaces around the spherical earth
     - Gravitational potential same on a surface

Speeds

- Measurement of speeds on ground - easy
  - Ground does not move or deform
- Measurement of speeds in the air – difficult
  - Air moves (i.e. wind) and deforms (compresses)

Speeds: Pitot-Static System

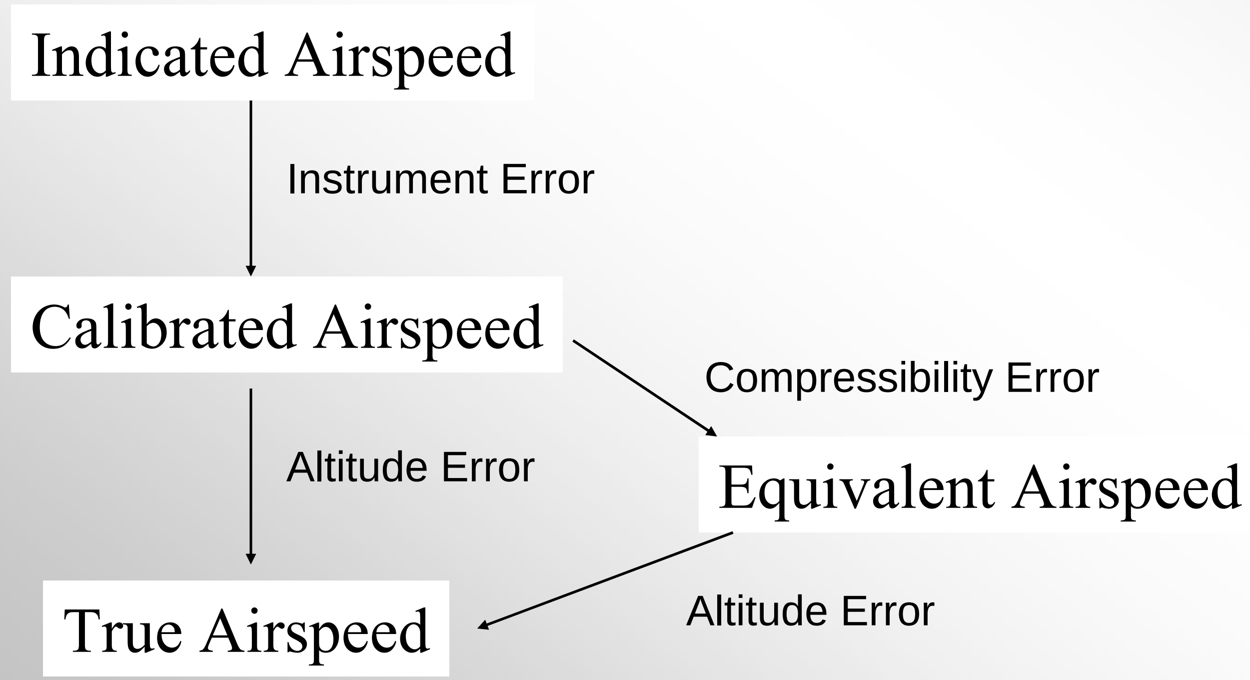


Speeds: Pitot-Static System

- Measures difference in air pressure between tip and side ports
  - Tip = Total Pressure = p_t
  - Side = Static Pressure = p_s
- Dynamic pressure = $q = p_t - p_s = \frac{1}{2} \rho V^2$
    - ρ = density (slugs/ft3) = 0.002377
    - V = True Airspeed (ft/sec)
  - Applies only at:
    - standard sea-level conditions
    - Speeds low enough not to air mass to compress

Speeds

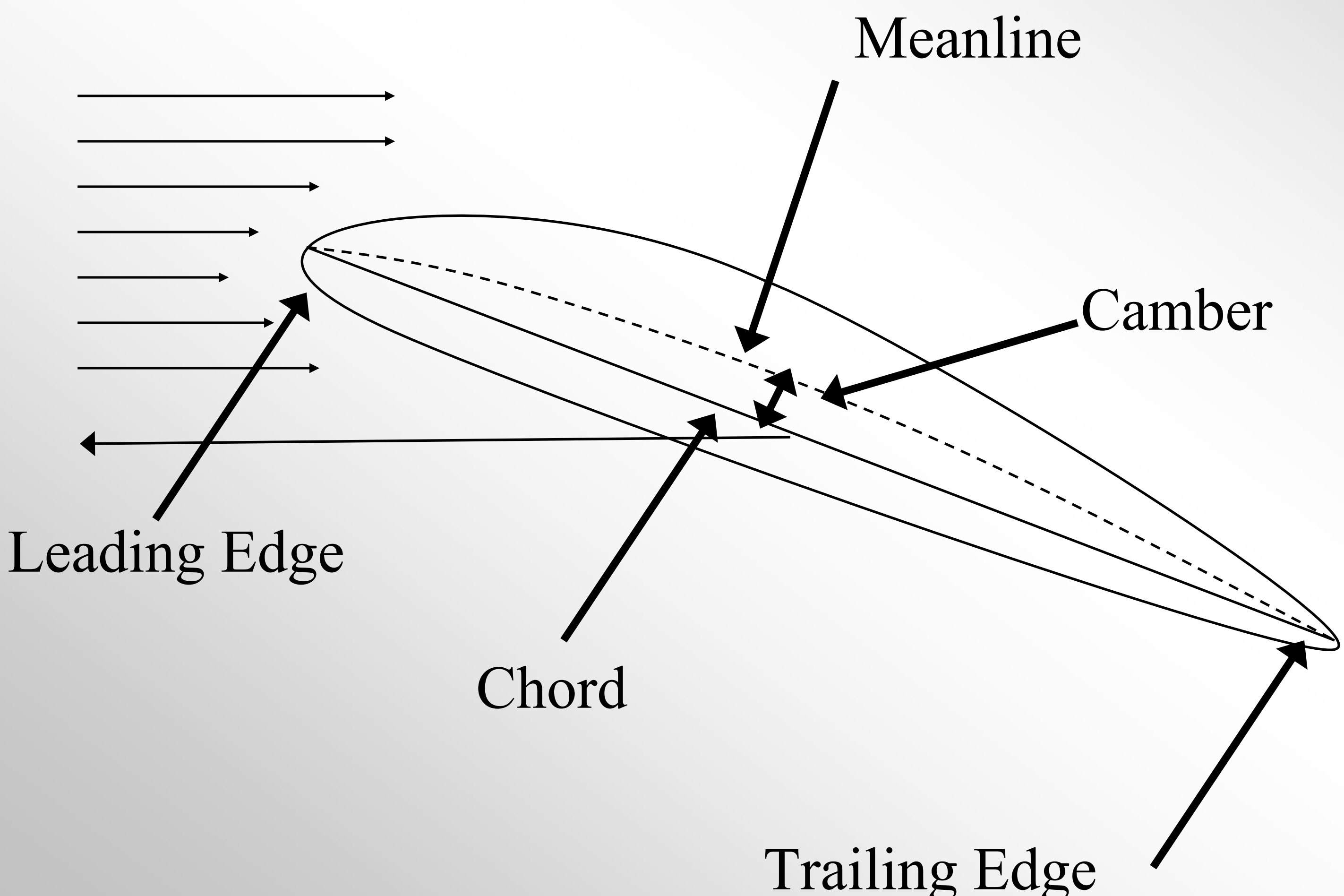
- Aircraft have high speeds and high altitude
- Pitot-static system calibrated at sea-level
- Distortions compensated



Speeds

- Airspeed Measurements:
  1. Indicated Airspeed
     – airspeed measurement from difference in pressures
  2. Calibrated Airspeed
     – Correcting for instrument errors
  3. Equivalent Airspeed
     – Corrected for Compressibility effects
  4. True Airspeed
     – Actual relative speed between aircraft and airmass
     – Corrected for difference in density at different altitudes

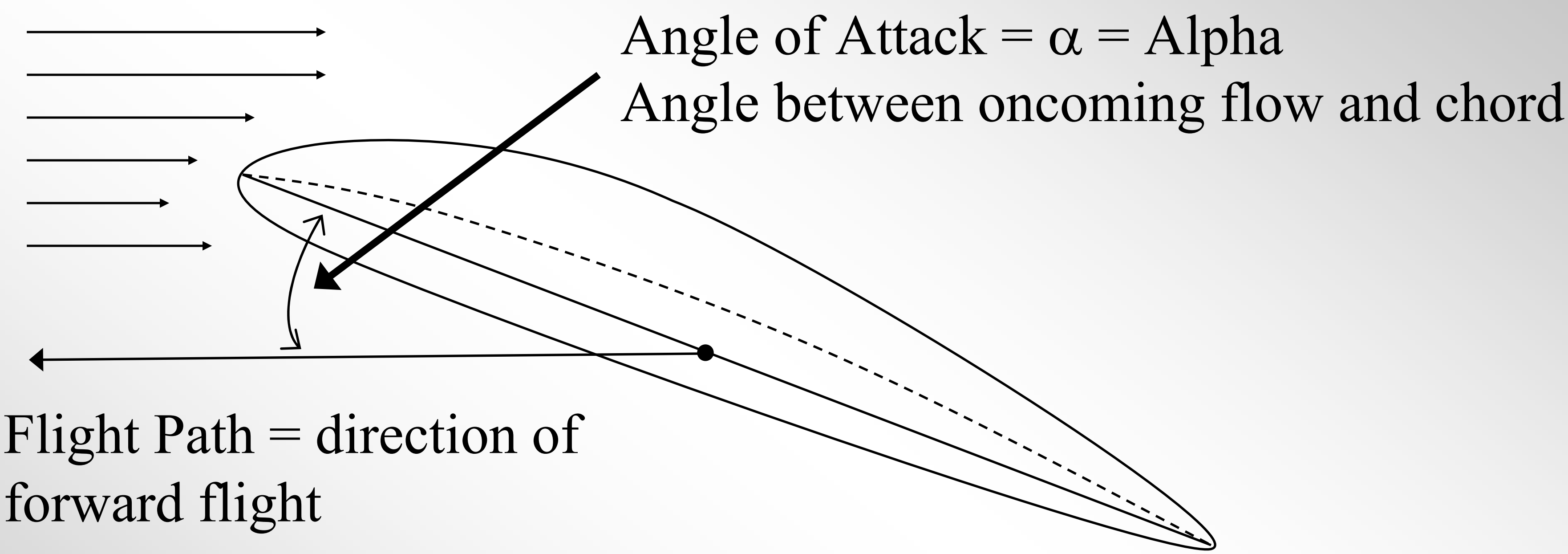
Wings



Wings

- Leading Edge
  - faces oncoming flow
- Trailing edge
  - opposite oncoming flow
- Chord
  - straight line from leading edge to trailing edge
- Meanline
  - Line midway between upper and lower surface
- Camber
  - Maximum difference between meanline and chord
  - *Symmetrical airfoil, camber = zero*

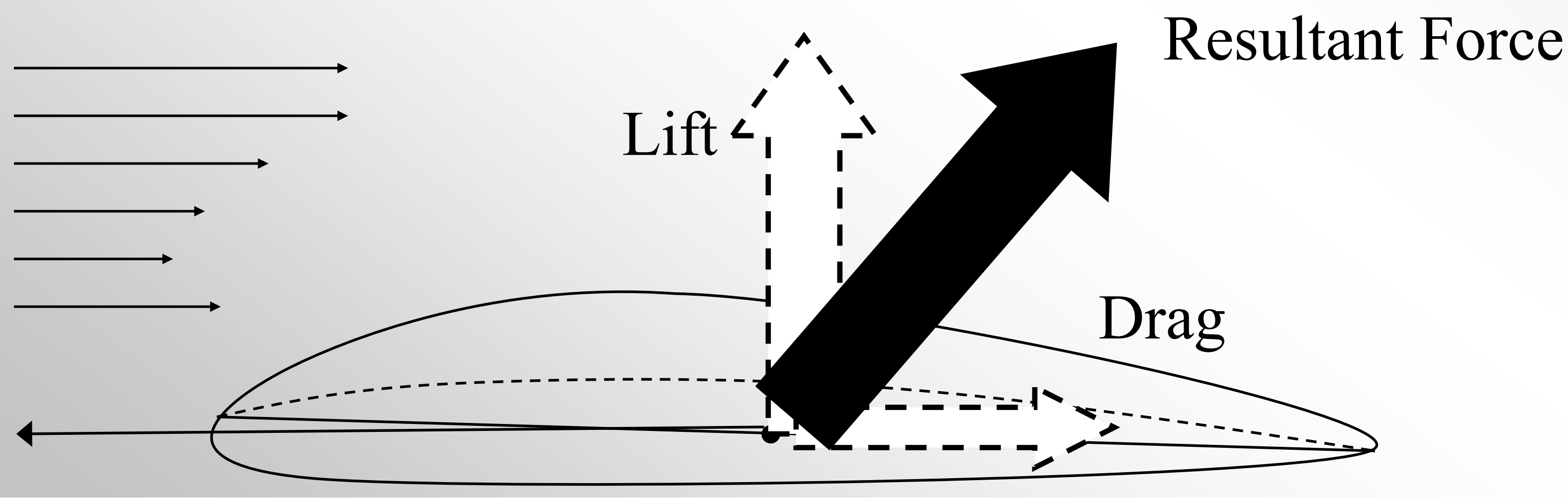
Wings



Angle of Attack = α = Alpha
Angle between oncoming flow and chord
Flight Path = direction of forward flight

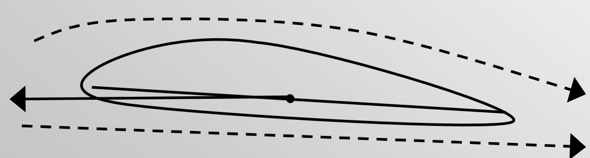
Lift & Drag

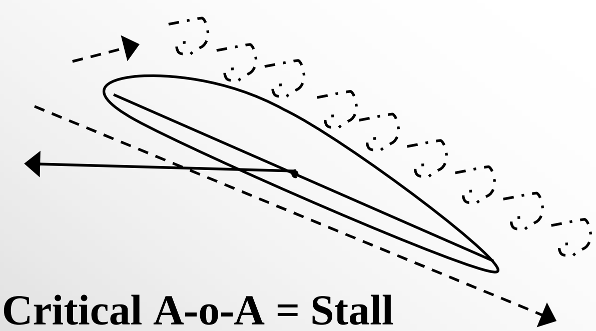
- Lift Force:
  - upward force created by wing moving through air
- Drag Force:
  - rearward force resists forward movement through air



Lift

- Strength of Lift determined by:
  1. Airspeed
  2. Angle of Attack
  3. Planform of Wing – shape of wing from above
  4. Wing Area
  5. Density of Air
- Lift increases an Angle-of-Attack increases, upto critical Angle-of-Attack (18º - 20º)



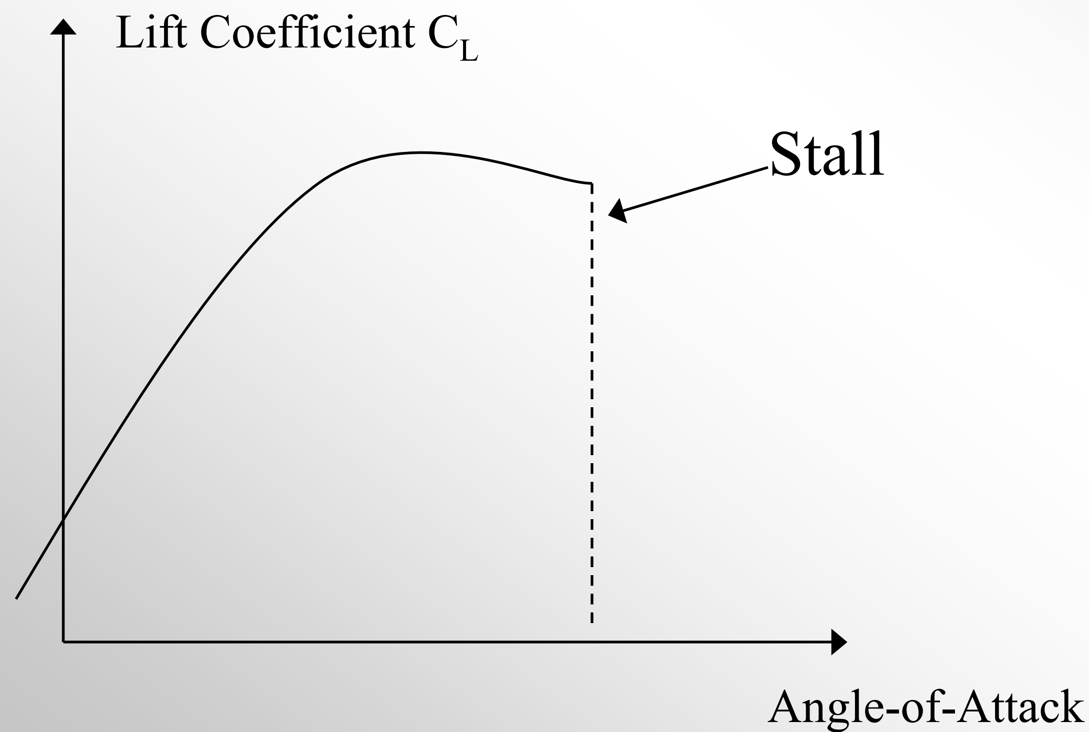


Critical A-o-A = Stall

Lift

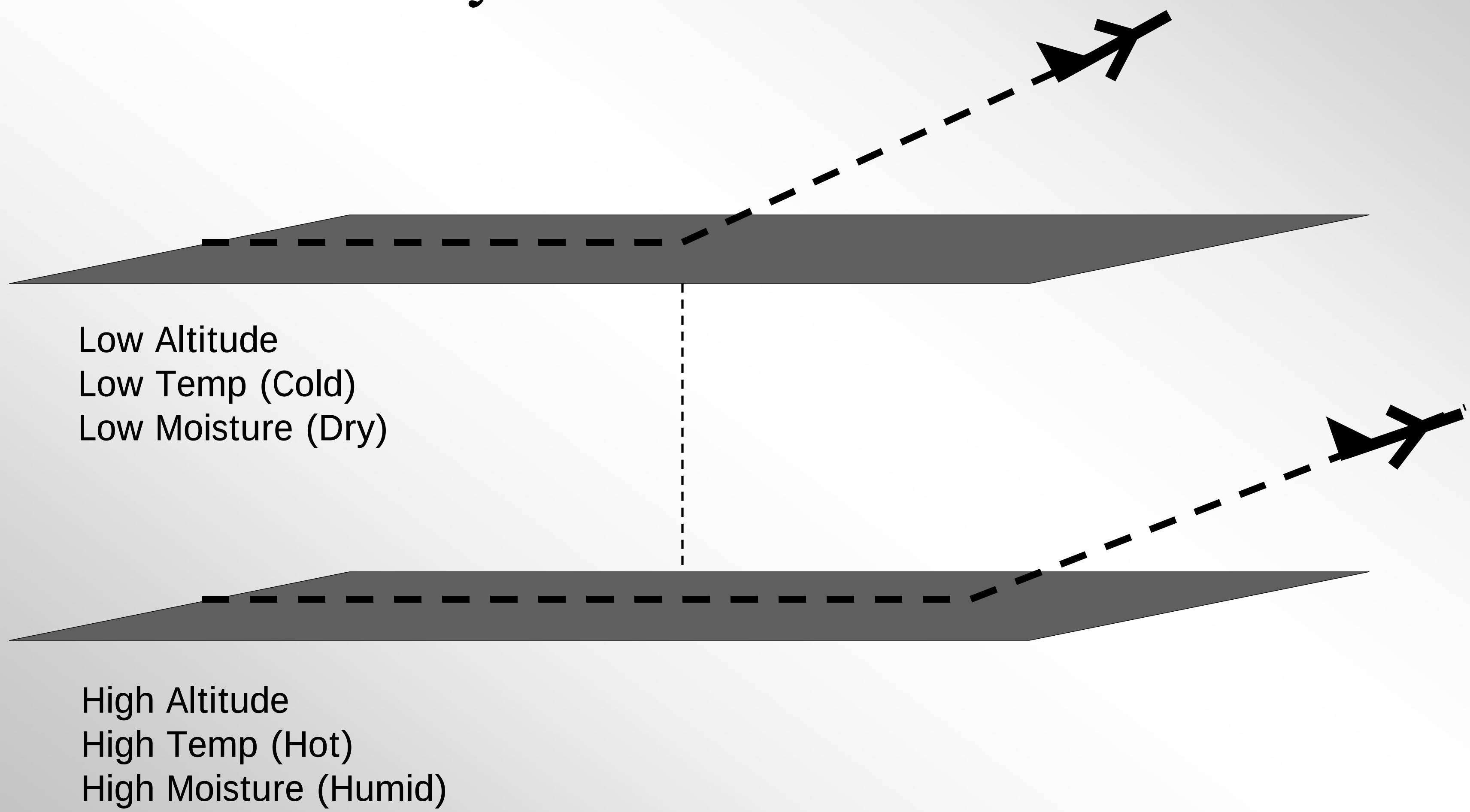
Effect of Angle-of-Attack

- Increased Angle-of-Attack increases left (until stall)



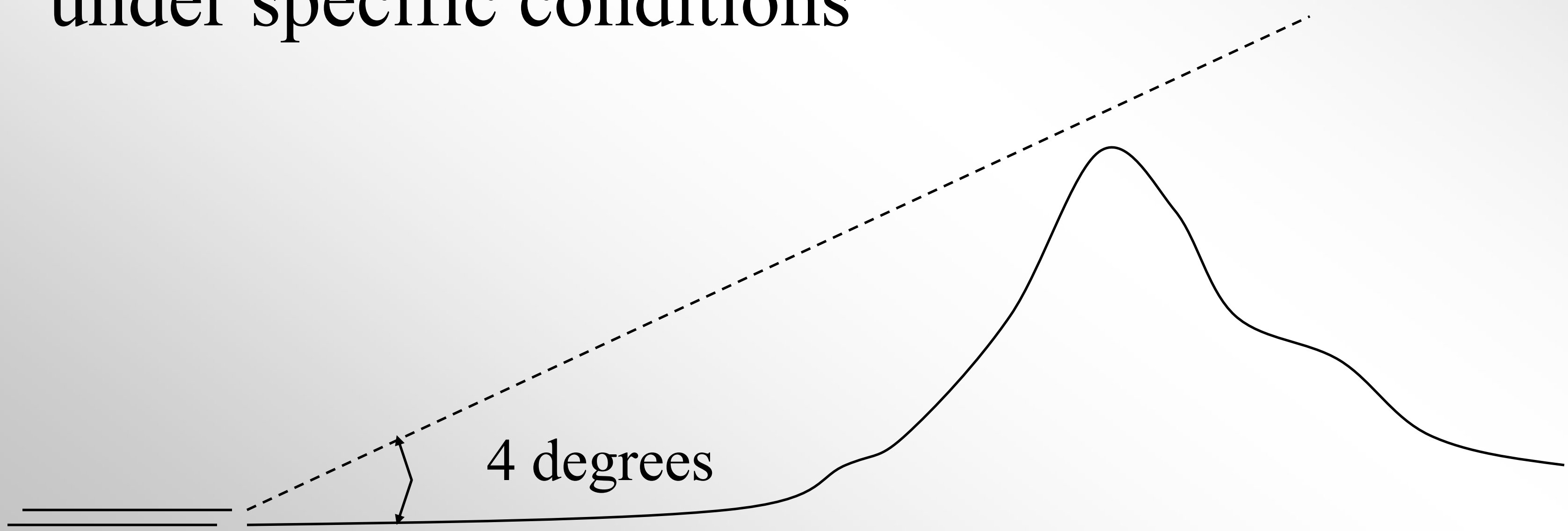
Lift

Effect of Density of Air

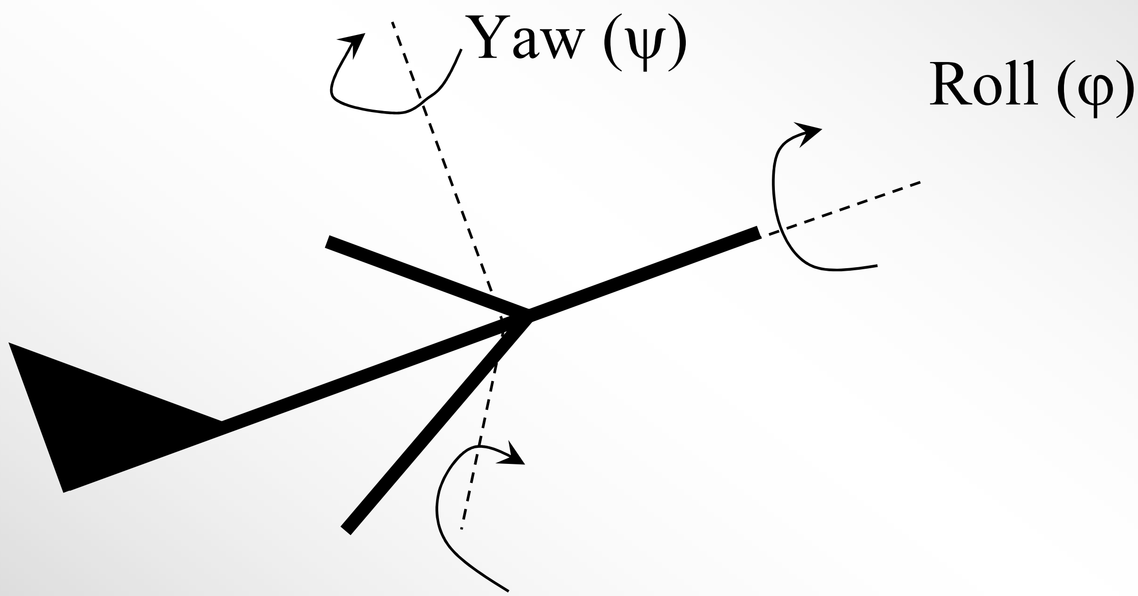


REAL WORLD PROBLEM

- Aircraft departing airport in valley must climb in excess of 4º flight path angle to avoid terrain.
- Compute Flight path angle (γ) for climb-out under specific conditions



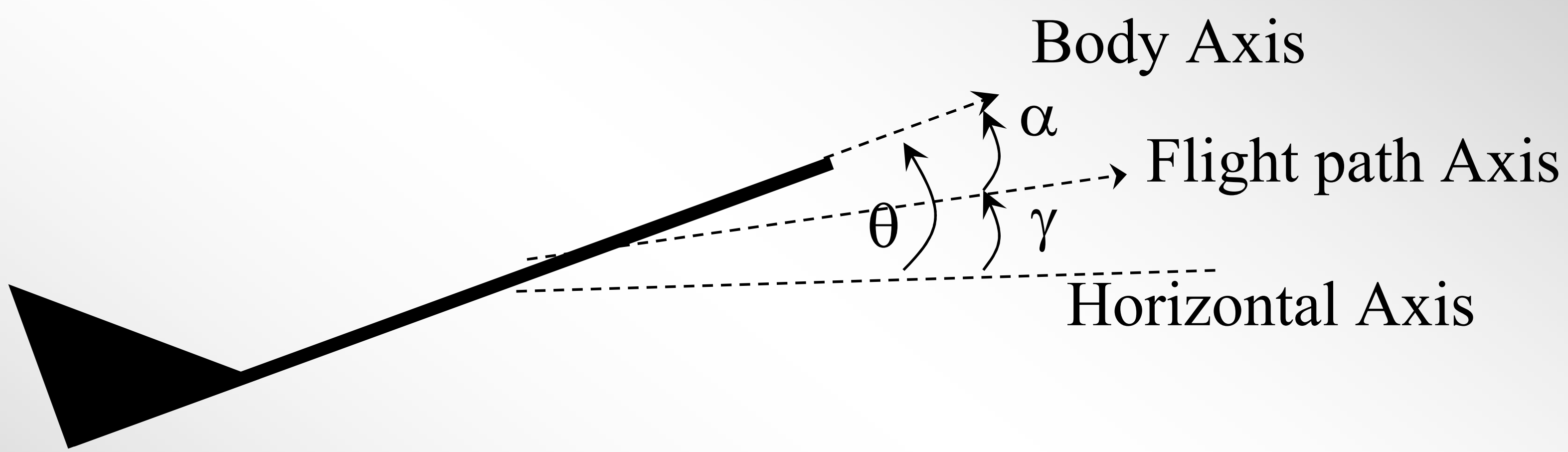
Angles of Rotation



Pitch (θ) =
Flight Path Angle (γ) + Angle of Attack (α)

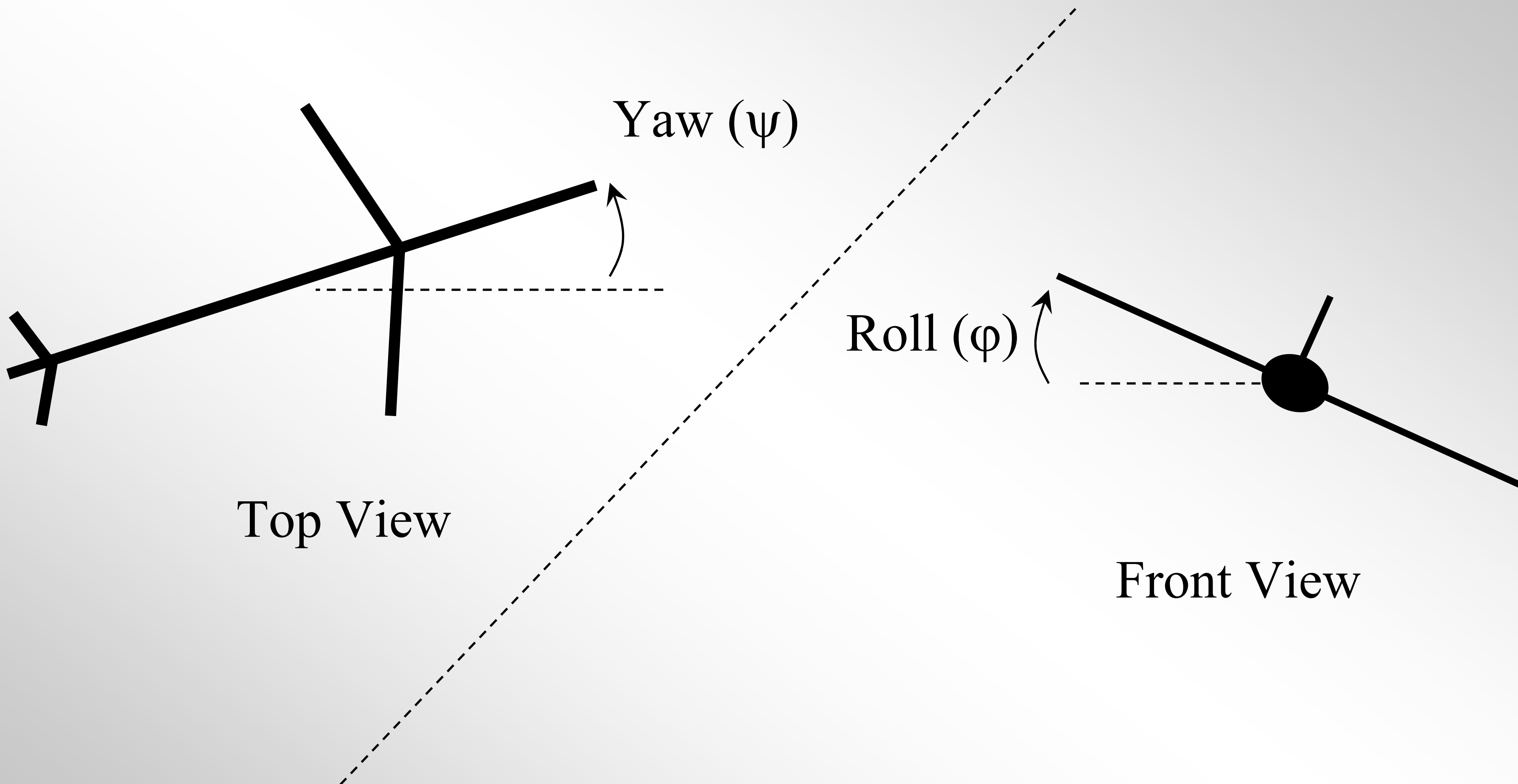
Exam Question: Name 3 angles of rotation

Axes and Angles of Rotation

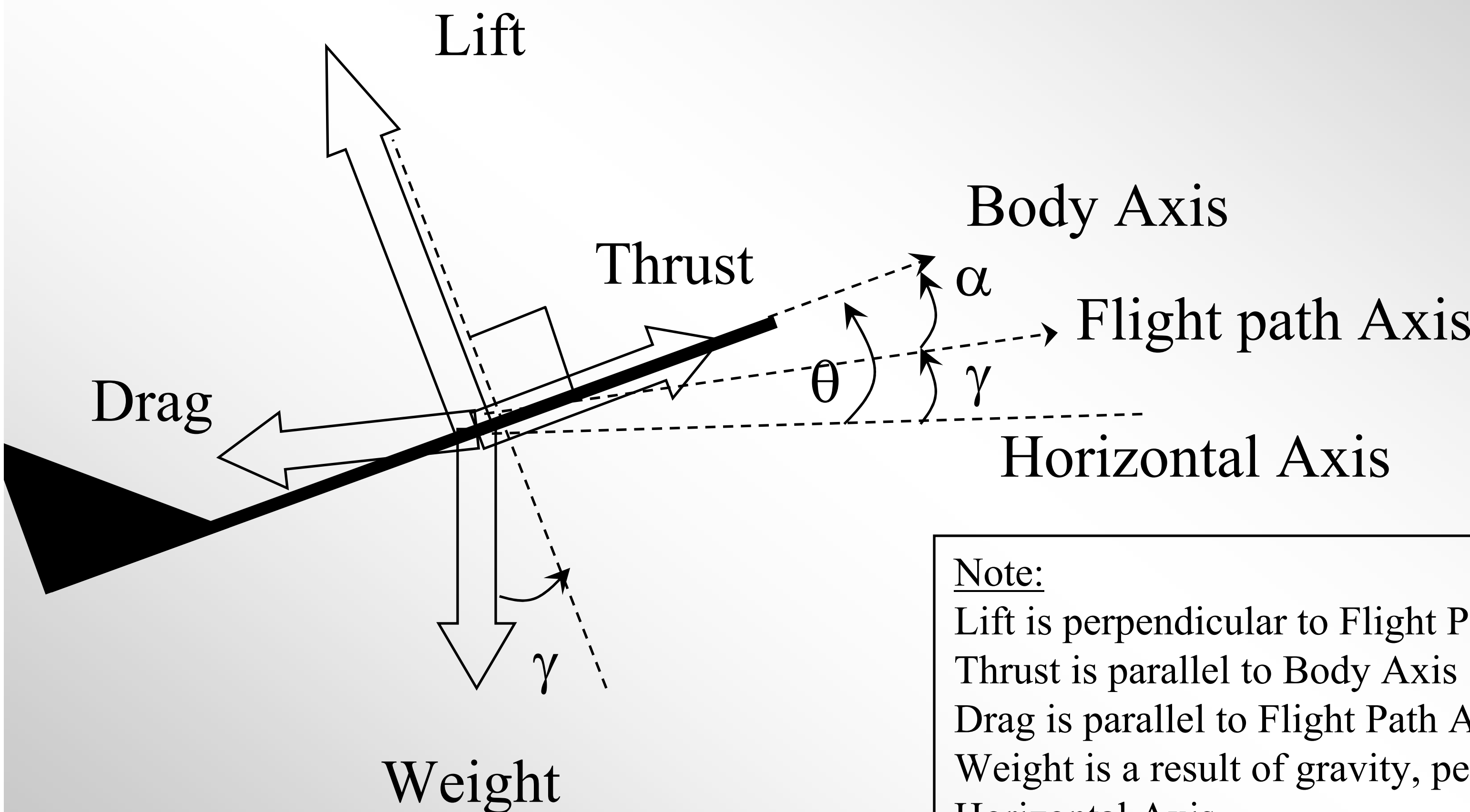


Pitch (θ) =
Flight Path Angle (γ) + Angle of Attack (α)

Axes and Angles of Rotation



Forces on Airplane (Vertical & Longitudinal)



Note:
Lift is perpendicular to Flight Path Axis
Thrust is parallel to Body Axis
Drag is parallel to Flight Path Axis
Weight is a result of gravity, perpendicular to Horizontal Axis

Exam Question: (1) Draw the Forces acting on an airplane in the Vertical and Longitudinal axes

Equations of Motion (Vertical & Longitudinal)

Mass * Acceleration = Σ Forces

Mass * Flight Path Acceleration (dV/dt) =

Thrust($\cos\alpha$) - Drag – Weight($\sin\gamma$)

- dV/dt - ft/sec
- Thrust, Drag, Weight – lbs
- α, γ - radians
- Mass = Weight/g, g=32.2 ft/sec^2

Exam Question: Given a diagram of the Forces acting on an airplane in the Vertical and Longitudinal axes, derive the equations of motion

Equations of Motion (Vertical & Longitudinal)

$M * dV/dt = T(\cos\alpha) - D - W(\sin\gamma)$

<u>Case 1: Level Flight, Constant Speed</u>

Level Flight - $\gamma = 0$

Constant Speed $dV/dt = 0$

$M * \quad 0 \quad = T(\cos\alpha) - D - 0$

$0 \quad = T(\cos\alpha) - D$

$-T(\cos\alpha) = -D$

$T(\cos\alpha) = D$

Thrust = Drag

Exam Question: (1) What is the relationship between Thrust and Drag for level flight and constant speed
(2) How much thrust is required to maintain level flight at constant speed

Equations of Motion (Vertical & Longitudinal)

$M * dV/dt = T(\cos\alpha) - D - W(\sin\gamma)$

Case 2: Level Flight, Increasing Speed (Accelerating)

Level Flight - $\gamma = 0$

Constant Speed $dV/dt > 0$

$M * dV/dt = T(\cos\alpha) - D - 0$

$(M * dV/dt) + D = T(\cos\alpha)$

Thrust = Drag + Force Required to Accelerate Mass

Exam Question: (1) What is the relationship between Thrust and Drag for level flight while increasing speed
(2) How much thrust is required to maintain level flight while increasing speed

Equations of Motion (Vertical & Longitudinal)

M * dV/dt = T(cosα) - D – W(sinγ)

<u>Case 3: Climbing, Constant Speed</u>

Level Flight - $\gamma > 0$

Constant Speed dV/dt = 0

M * 0 = T(cosα) - D – W(sinγ)

W(sinγ) + D = T(cosα)

Thrust = Drag + Force Required to Overcome Weight (for selected Flight Path Angle)

Maximum Angle for Climb (γMax) **is determined by Max Thrust, Weight and Drag**

Exam Question: What parameters determine the Maximum Climb Angle (γ_{Max}). Show equation

Equations of Motion (Vertical & Longitudinal)

Problem:

Aircraft departing airport in valley must climb in excess of 4º flight path angle to avoid terrain. Compute Flight path angle (γ) for climb with Drag = 6404 lbs, TAS = 634 ft/sec, W=100,000lbs. T=19500. Assume $\alpha = 0$, no winds.

$W(\sin\gamma) + D = T(\cos\alpha)$;

$\sin\gamma = (T(\cos\alpha) - D)/W$;

$\cos\alpha = \cos(0) = 1$;

$\sin\gamma = (19500(1) - 6404\text{lbs})/100{,}000\text{lbs}$

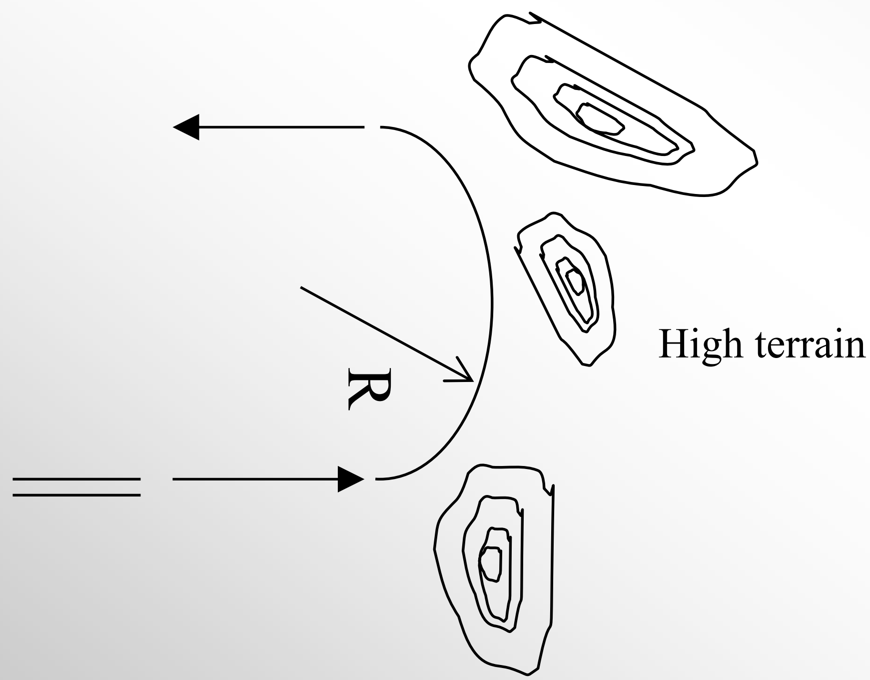
$\sin\gamma = 0.131$ radians

γ = Inverse sin (0.131radians * (360º /2Π)) = 7.5º

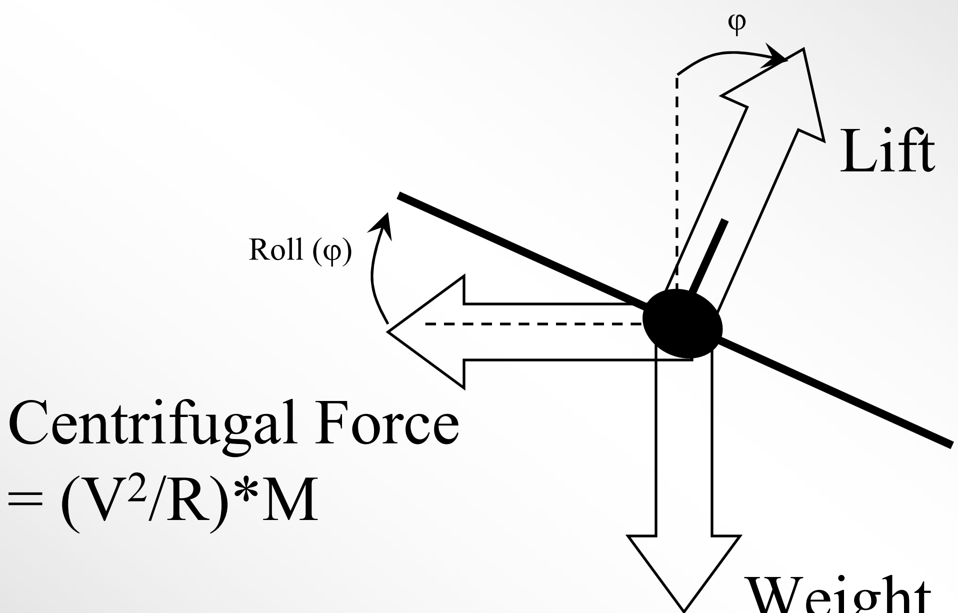
REAL WORLD PROBLEM

Problem:

Aircraft departing an airport located in a valley must make 180º turn of <u>no</u> more than 4nm turn radius to avoid high terrain under specific conditions. What bank angle is sufficient?



Forces on an Airplane (Vertical and Lateral)



Notes:
Un-accelerated turn
R = Radius of Turn

Exam question: (1) Draw a free-body diagram of an aircraft in the vertical/lateral axes. (2) Identify all axes. (3) Identify all forces. (4) Derive the equations of motion.

Equations of Motion (Vertical & Lateral)

ΣForces in Vertical Axis:

- $L(\cos\varphi) = W$, ➔ $L = W/\cos\varphi$

To maintain level flight, Lift must exceed Weight

Equations of Motion (Vertical & Lateral)

ΣForces in Lateral Axis:

$(V^2/R)*M = L(\sin\varphi)$

$(V^2/R)*W/g - L(\sin\varphi) = 0$ (1)

ΣForces in Vertical Axis:

$L(\cos\varphi) - W = 0$

$L = W/(\cos\varphi)$ (2)

- Substitute equation (2) into equation (1)

$(V^2/R)*W/g - W(\sin\varphi)/(\cos\varphi) = 0$

- Replace W with mg, and $(\sin\varphi)/(\cos\varphi) = (\tan\varphi)$

$(V^2/R)*mg/g - mg(\sin\varphi)/(\cos\varphi) = 0$

$(V^2/R)*m - mg(\tan\varphi) = 0$

- Solve for $\tan\varphi$

$\tan\varphi = (V^2/R)*(1/g)$

Solve for R

$R = V^2/(g \tan\varphi)$

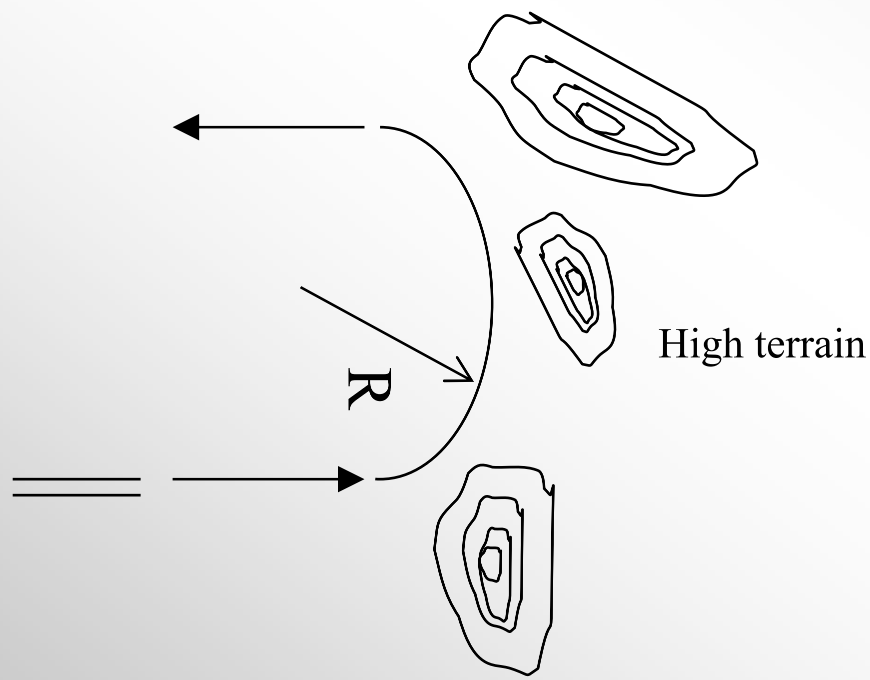
Turn Radius is determined by Speed (V) and Roll Angle (φ)

Note: φ is in radians, degrees to radians = 2Pi/360 , $g = 32.2$ ft/sec^2

Equations of Motion (Vertical & Lateral)

Problem:

Aircraft departing an airport located in a valley must make 180º turn of <u>no</u> more than 4nm turn radius to avoid high terrain. Aircraft speed (V) is 140 knots CAS (= 255 fps TAS). Will 15º roll angle be enough?



Equations of Motion (Vertical & Lateral)

Solution:

$R = V^2/(g \tan \varphi)$

$R = (255 ft/sec)^2 / (32.2 ft/sec) (\tan (15^o * 2Pi/360^o))$

R = 7548 ft

Convert feet to n.m. (1nm = 6076 ft)

R = 1.24 nm