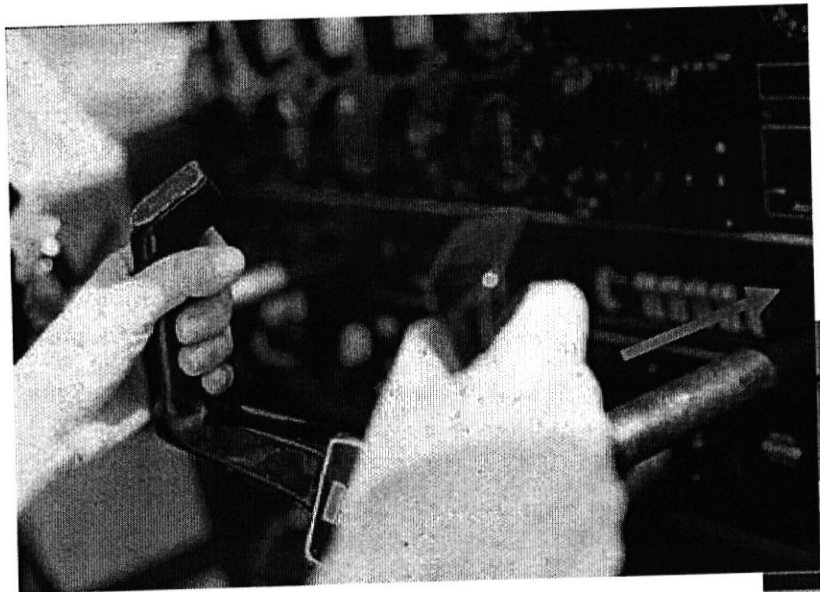
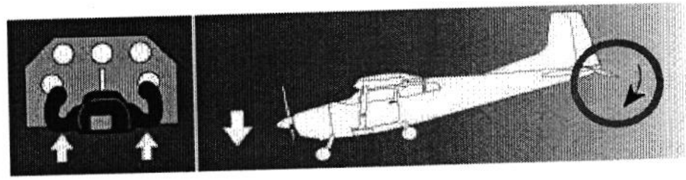
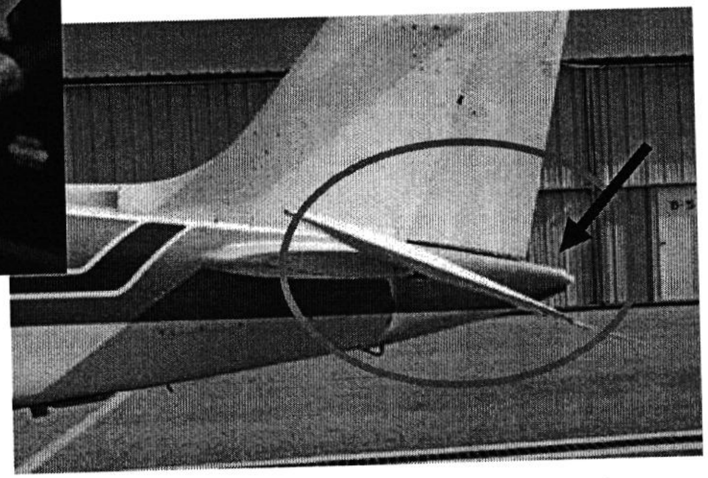
FLIGHT CONTROLS

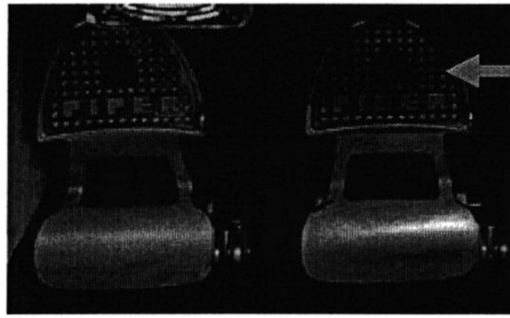




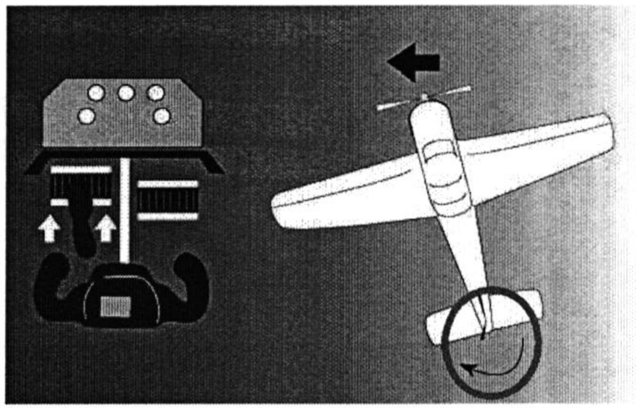


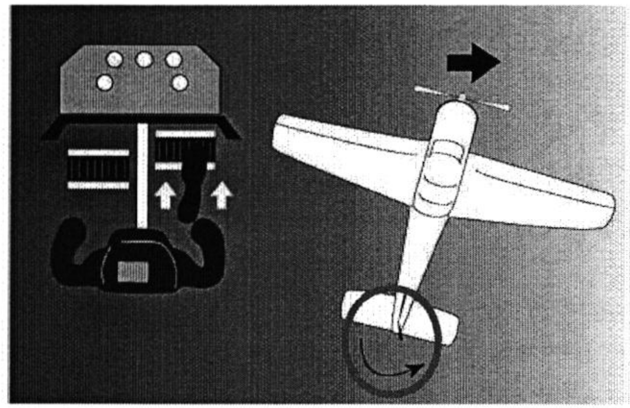
Pushing forward moves the elevator DOWN, moves the nose DOWN to descend.

FLIGHT CONTROLS



Brakes are located at the top or "toe" of the pedal





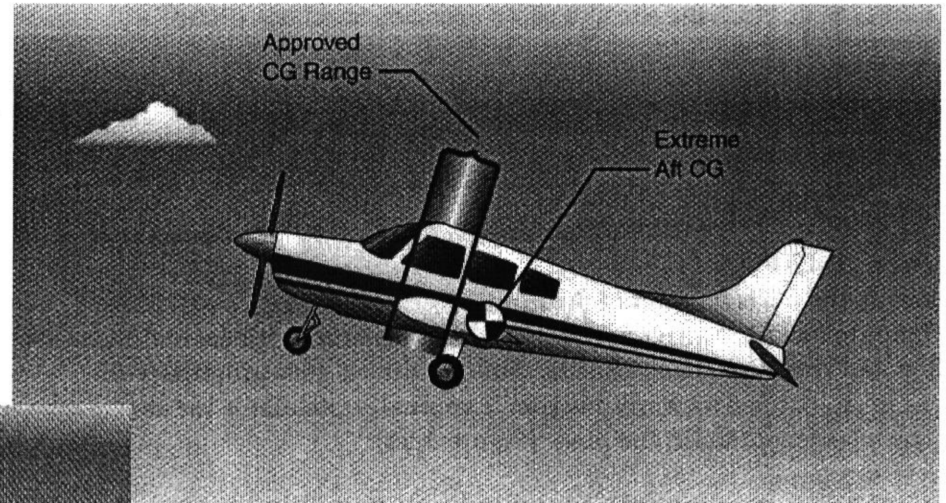
Pilots use rudder pedals on the floor to move the rudder LEFT or RIGHT to help the airplane turn.

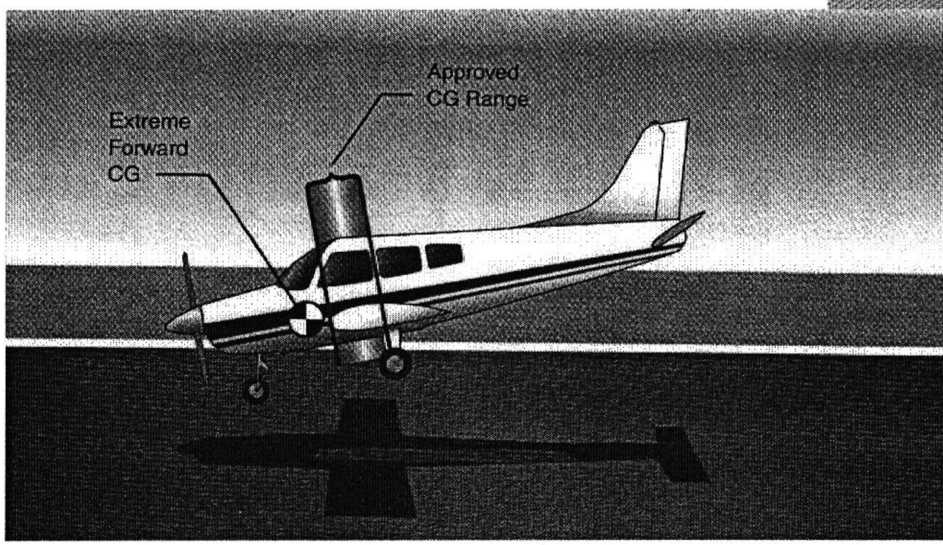
Stick Force

- Force exerted by pilot to move the control surface
  - Stick Force Gradients
- Trim Tabs

Stability and Control

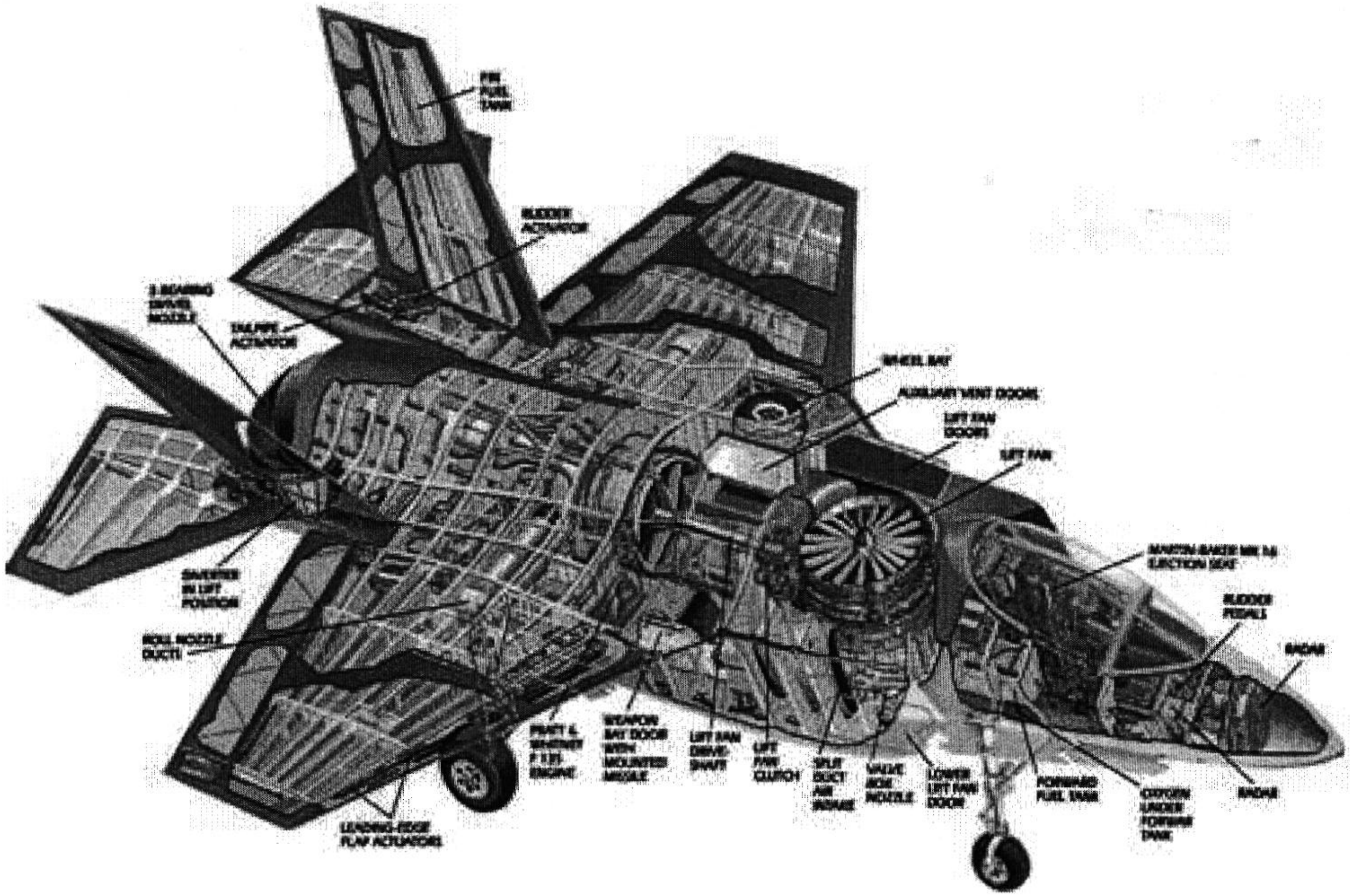
- Inherently stable airplane returns to its original condition after being disturbed. Requires less effort to control



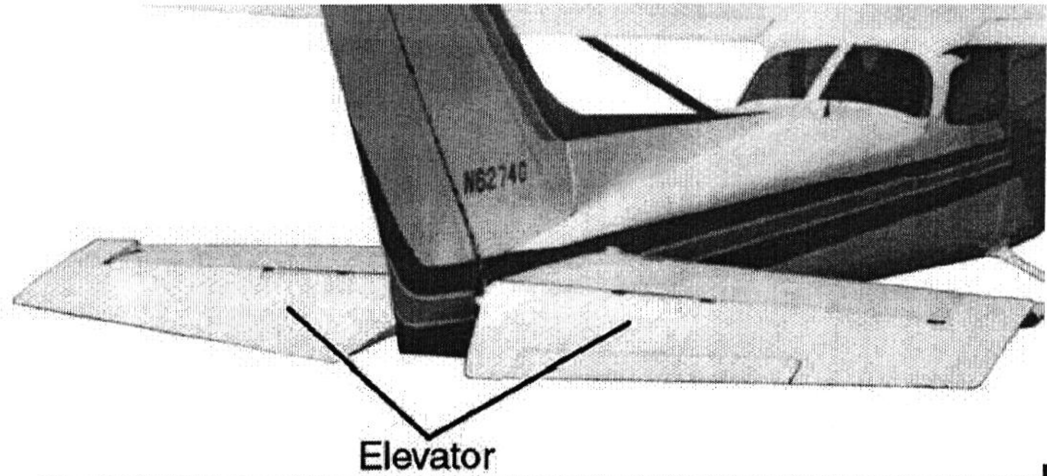


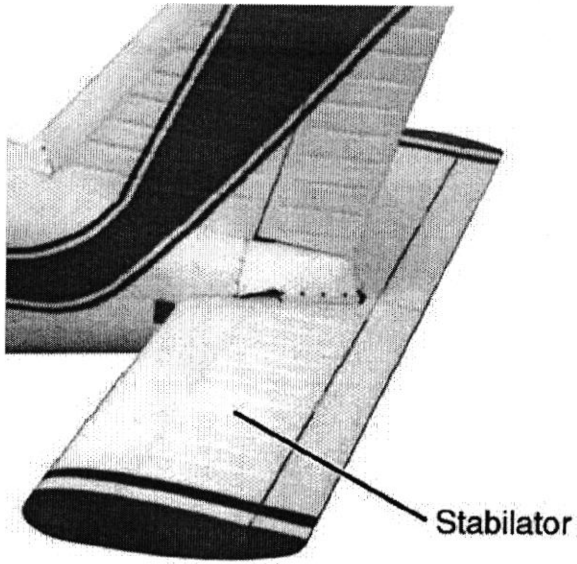
- Center of Gravity concerns:
  - Unable to compensate with elevator in pitch axis
  - Weight and Balance becomes critical – taught in a coming lecture

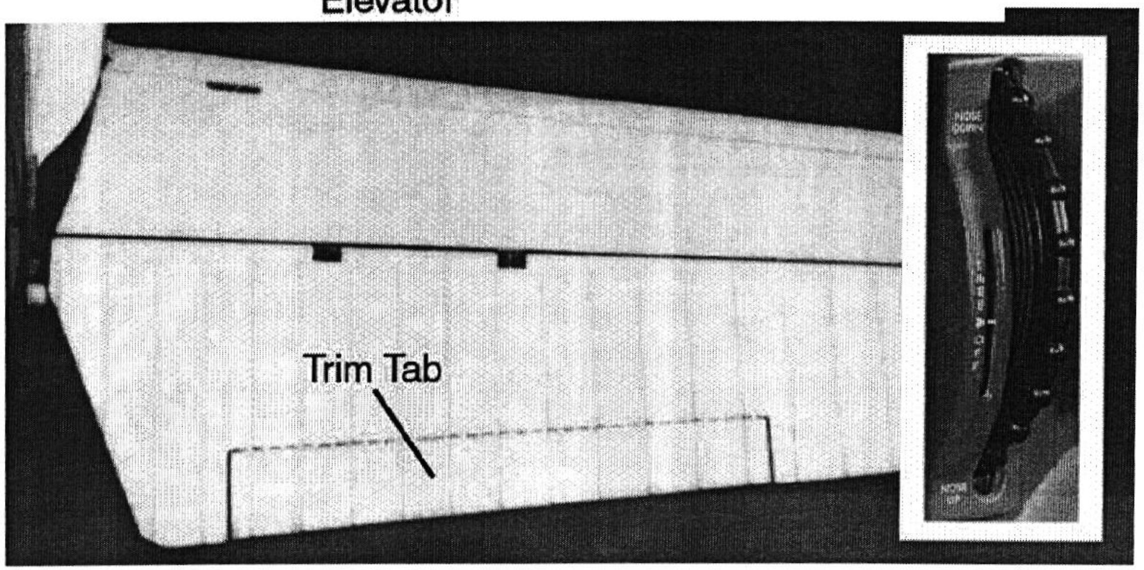
Control Surfaces and their Function



Aerodynamic Surfaces

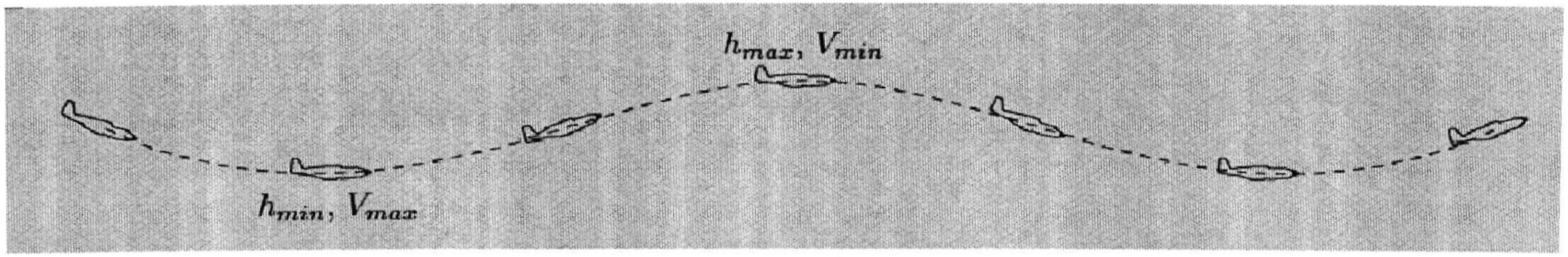




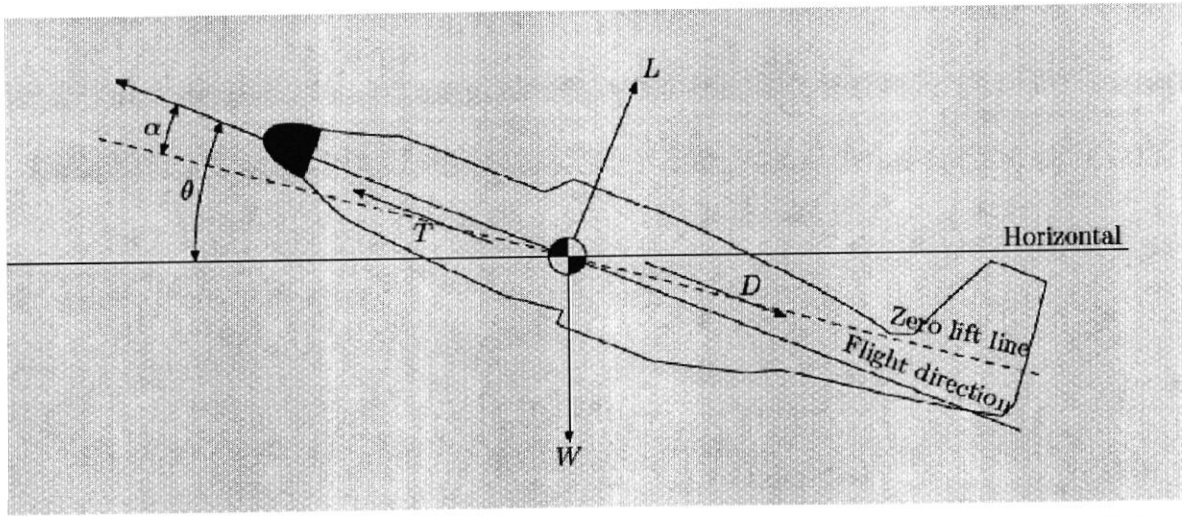


Phugoid Motion

- Phugoid mode is a lightly damped long period oscillation.
- The incidence is almost constant and the aircraft varies altitude at constant energy, trading potential for kinetic and back again



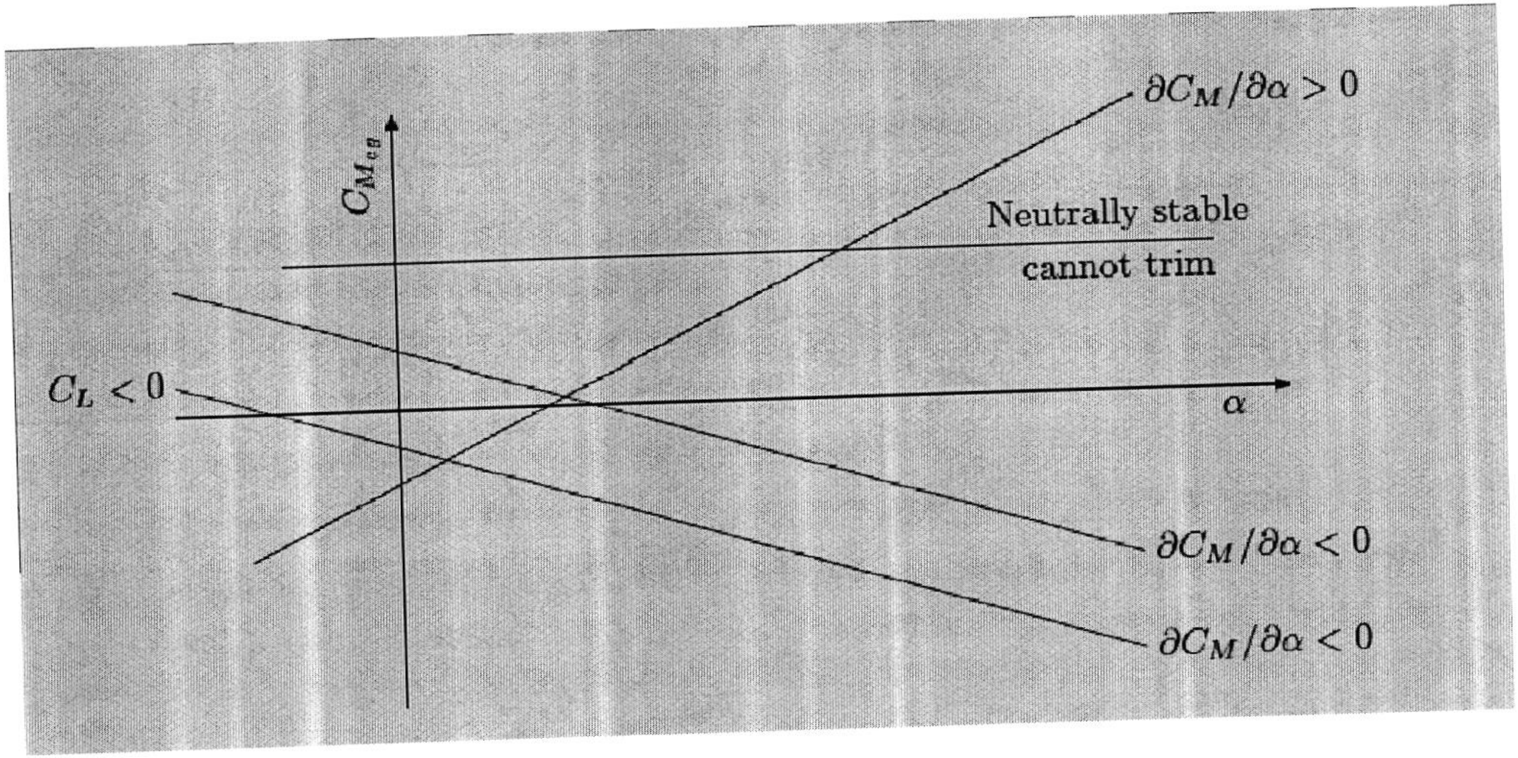
Trim and Stability



$$\text{Perpendicular:} L - W\cos\theta = 0,$$
$$\text{Parallel:} T - D - W\sin\theta = 0,$$
$$\text{Moments about the c.g.:} M_{cg} = 0.$$

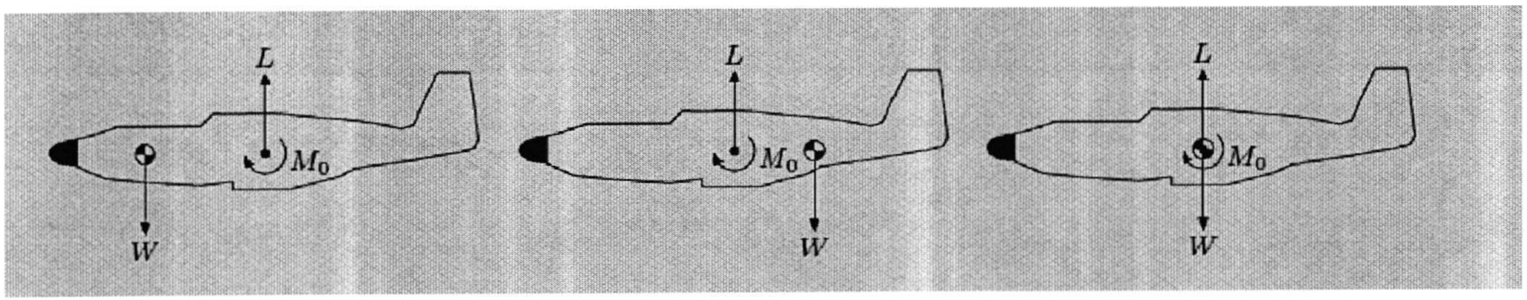
Stability and Moment coefficient variation

- How the moment coefficient CM varies with angle-of-attack determines the stability of the aircraft

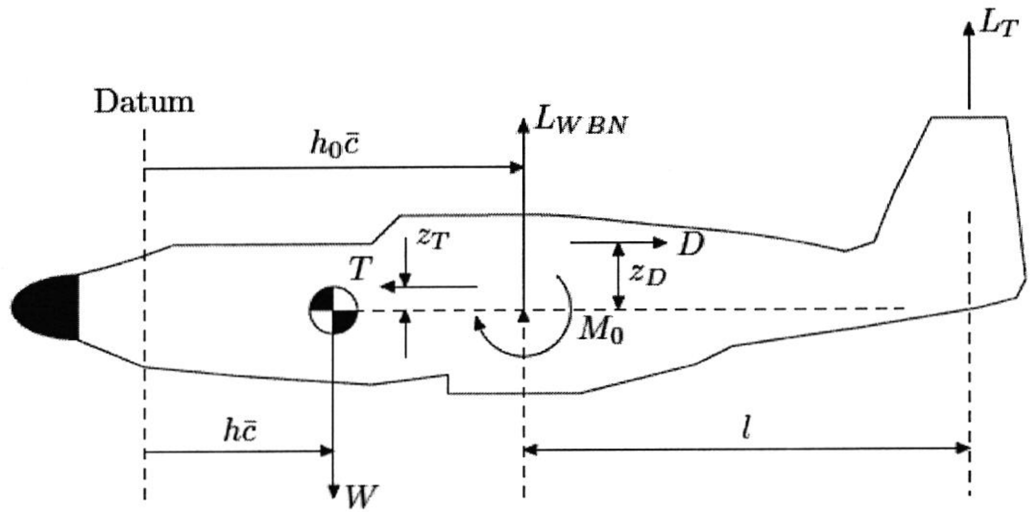


Effect of C. G. Position on Stability

- If the c.g. is forward of the aerodynamic centre, dMcg/dα will be negative and the aircraft will therefore be statically stable.
- If the c.g. is aft of the aerodynamic centre, dMcg/dα will be positive and the aircraft will therefore be statically unstable.
- If the c.g. is at the aerodynamic centre, dMcg/dα will be zero and the aircraft will therefore be neutrally stable.



Forces and Locations Conventional A/c



where $h\bar{c}$ is the distance of the c.g. aft of a reference point and $h_n\bar{c}$ is the distance of the neutral point aft of a reference point.

$$
\begin{aligned}
M_{cg} &= M_0 - L_{WBN}(h_0 - h)\bar{c} - L_T((h_0 - h)\bar{c} + l) - Tz_T + Dz_D \\
&= M_0 - (h_0 - h)\bar{c}(L_{WBN} + L_T) - L_T l - Tz_T + Dz_D \\
&= M_0 - (h_0 - h)\bar{c}L - L_T l - Tz_T + Dz_D.
\end{aligned}
$$

$$M_{cg} = M_0 - (h_0 - h)\bar{c}L - L_T l.$$

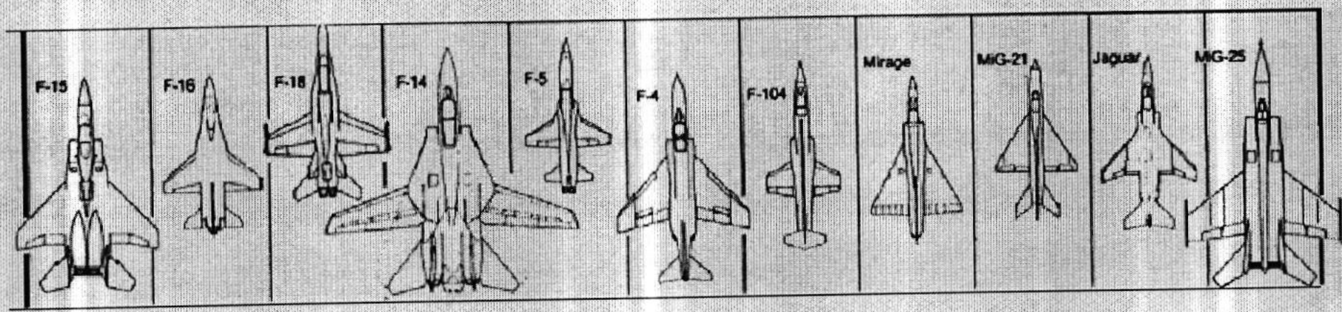
Assuming T, D and Z_T and Z_D are small

Forces and Locations Conventional A/c

- L is bigger than D and T so it is a fair to drop the last 2 terms giving. $M_{cg} = M_0 - (h_0 - h)\bar{c}L - L_T l.$

- Using non-dimensional coefficients and defining tail volume ratio as $\overline{V} = \frac{S_T}{S}\frac{l}{\bar{c}}$

Typical values for Tail volume ratio



0.16 0.20 0.17 0.18 0.17 0.13 0.30 0.14 0.26 0.23 0.19

Typical Values for Tail Volume Ratio

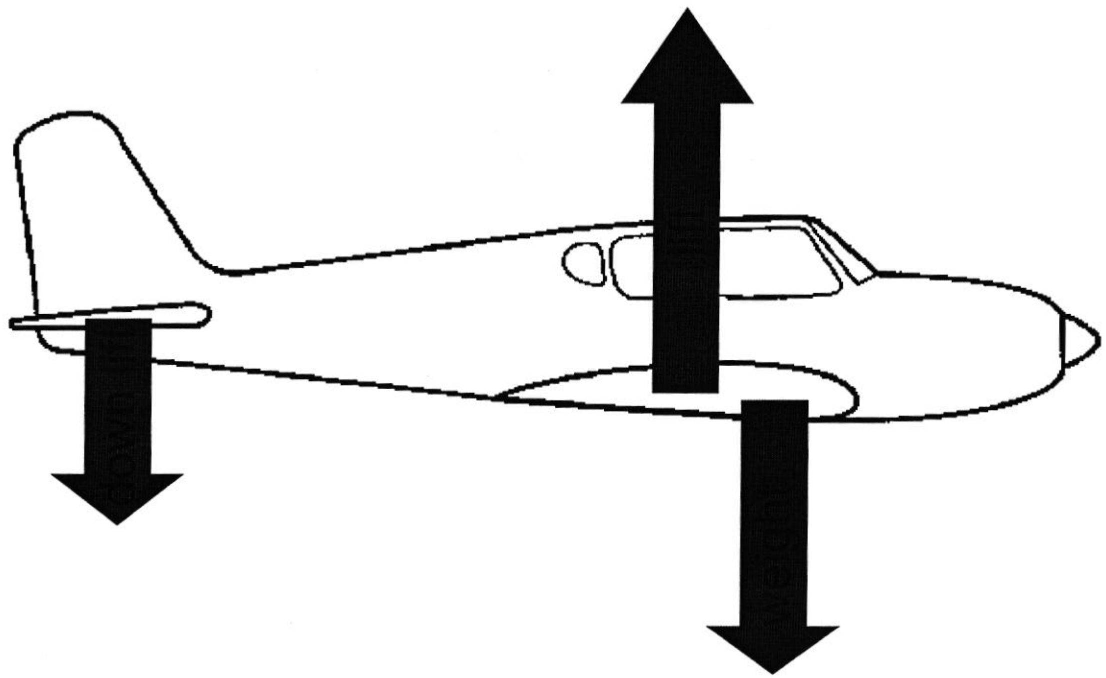
$$C_{M_{cg}} = C_{M_0} - (h_0 - h)C_L - \overline{V}C_{L_T}$$

Note : For Trim, LHS should be zero

This equation can answer the questions

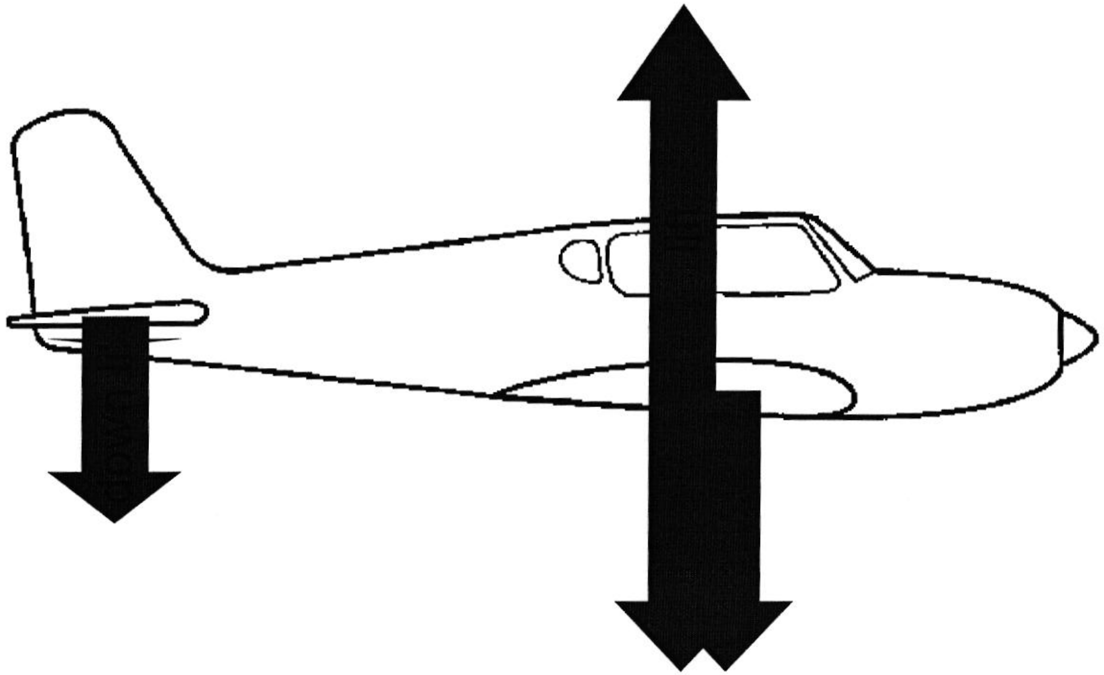
- "What is the lift required at the tailplane for trim." or
- "Calculate the elevator angle required for trim."

Longitudinal Stability



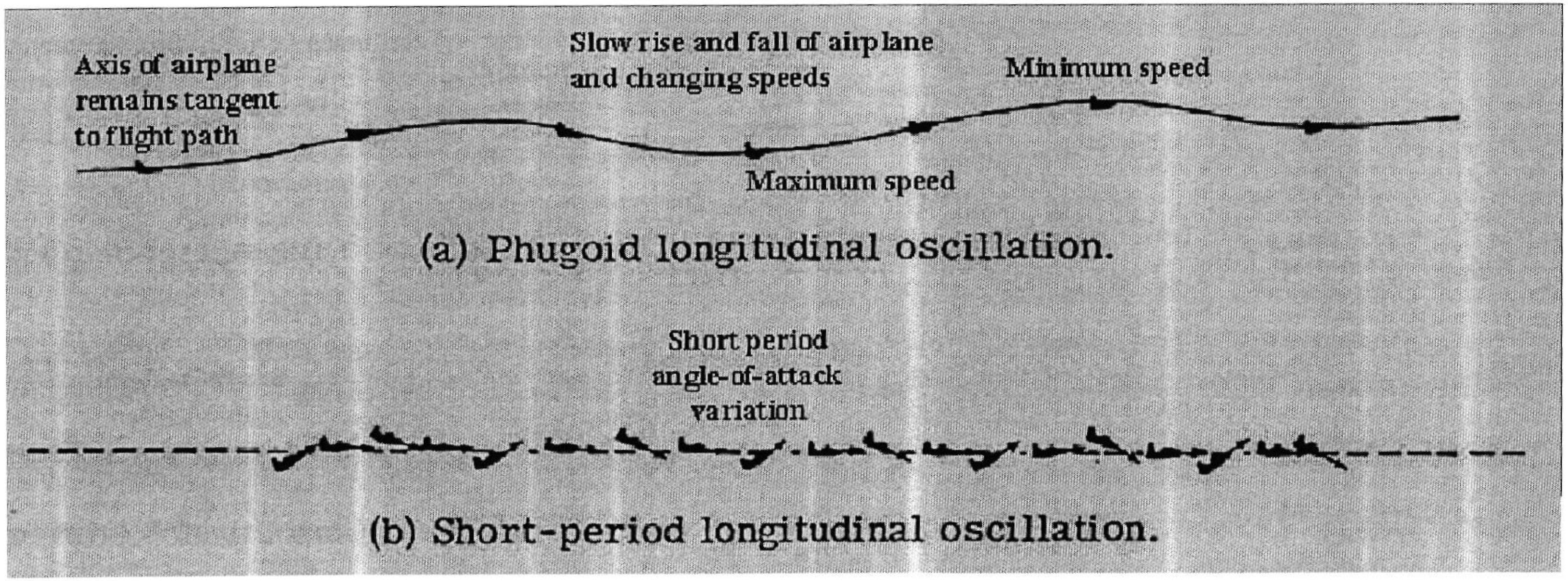
- Static stability (tendency to return after control input)
  - up elevator increases downward lift, angle of attack increases;
  - lift increases, drag increases, aircraft slows;
  - less downward lift, angle of attack decreases (nose drops).

Aside: CG and Center of Pressure Location



- Aft CG increases speed:
  - the tail creates less lift (less drag);
  - the tail creates less down force (wings need to create less lift).
  - This also decreases stall speed (lower angle of attack req'd).

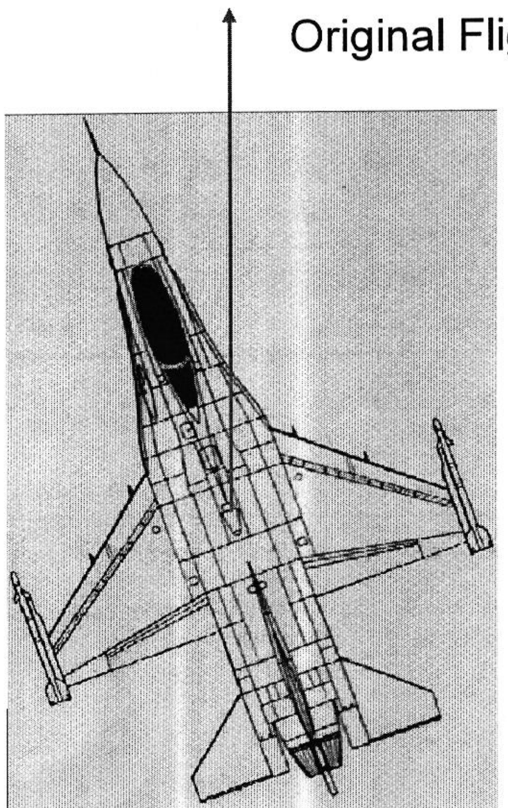
Longitudinal Modes

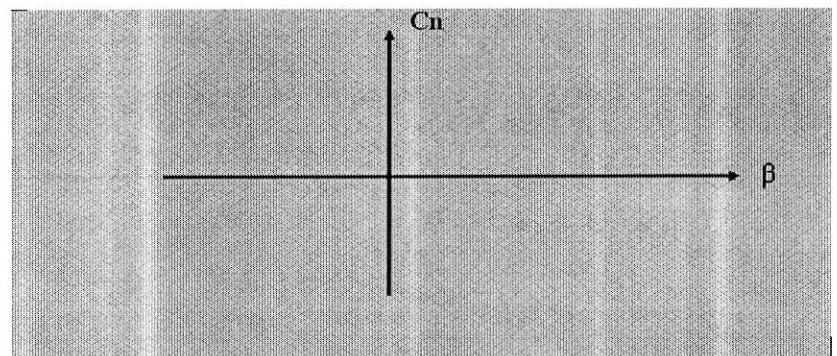


Lateral Stability

Lateral static stability : refers to the ability of the aircraft to generate a yawing moment to cancel disturbances in sideslip V
Question : Which direction should the yawing moment act to align the aircraft with the velocity vector ?

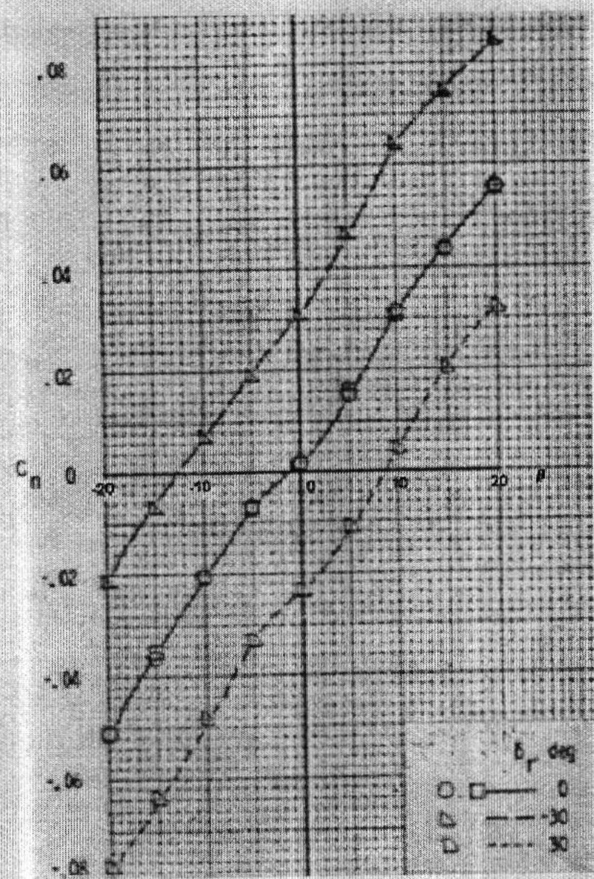
Original Flight Direction





1. Cn should be an anti symmetric function of β
2. $\partial C_n / \partial \beta$ (denoted as C_{n_β}) must be > 0 for lateral static stability

Typical Experimental results



Observe

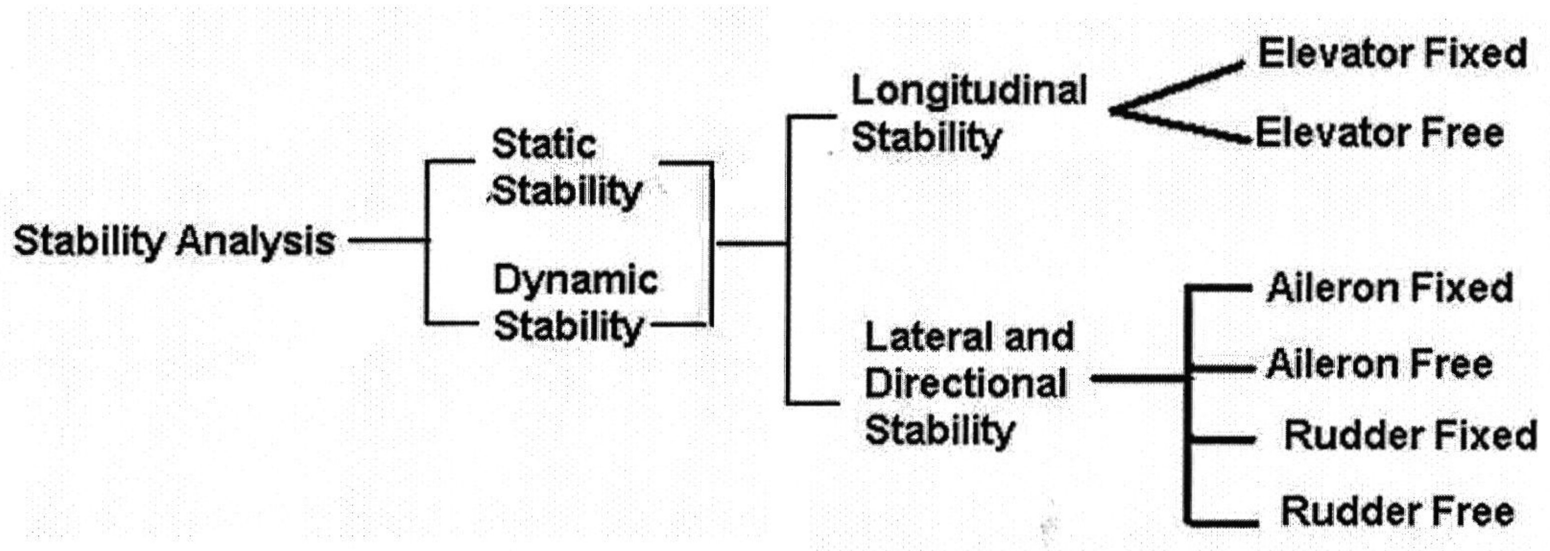
1. Positive slope

2. Quasi linear variation

3. Effect of rudder

Source : NASA TN D6425

Stability Analysis



Elevator, Aileron & Rudder Fixed ➔ These are at a fixed angle during the motion
Elevator, Aileron & Rudder Free ➔ They are free to adjust as the motion goes on

Equilibrium, Stability and Control

- ***Equilibrium*** : When all forces (Lift, Weight, Drag, Thrust) and moments about the c.g cancel out
- ***Stability*** : An airplane is said to be statically stable if, following a disturbance, forces and moments are produced by the airplane which tend to reduce the disturbance by itself.
- ***Control*** : Forces and moments produced by pilot inputs to bring the airplane back to equilibrium after disturbance.

Equilibrium, Stability and Control

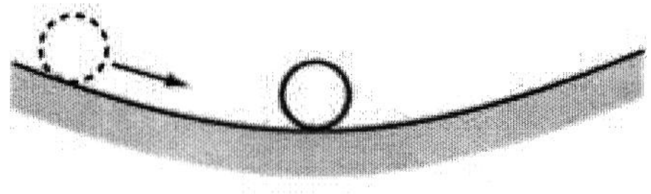
- Stability and controllability are different
  - Stability : If a system is in equilibrium, ability to maintain that state
  - Controllability : the ability to change the equilibrium state
- Very stable airplane will resist changes in it's attitude and hence, will be difficult to control.
- Military airplanes, for which maneuverability is one of the requirements, have lower levels of stability than civil airplanes.
- Stability is desirable but not necessary in piloted planes

Stability

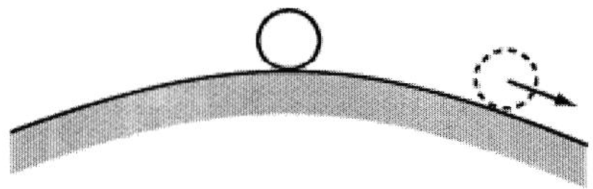
- An airplane may be stable under some conditions of flight and unstable under other conditions.
- For instance, an airplane which is stable during straight and level flight may be unstable when inverted, and vice versa.
  - This stability is sometimes called inherent stability.
- Modern combat aircraft are deliberately made to be inherently unstable, as this increases their manoeuvrability (Eg TEJAS)
- This requires a sophisticated automatic artificial stabilisation system, which has to be totally reliable.

Static Stability – 1 DOF

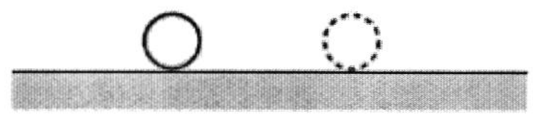
Statically stable. If the forces and moments on the body caused by a disturbance tend initially to return the body toward its equilibrium position, the body is ***statically stable***.



Statically unstable. If the forces and moments are such that the body continues to move away from its equilibrium position after being disturbed, the body is ***statically unstable***.

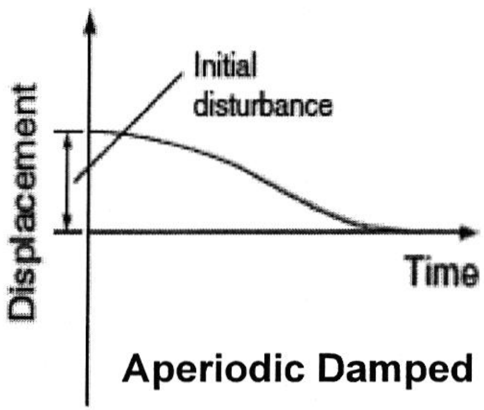


Neutrally stable. If the body is disturbed but the moments remain zero, the body stays in equilibrium and is ***neutrally stable***

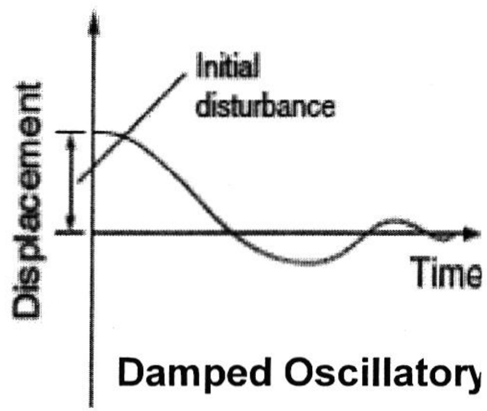


Dynamic Stability

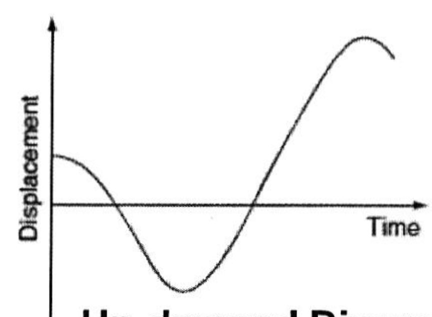
1. ***Dynamic stability*** deals with the time history of the vehicle's motion after it initially responds to its static stability.
2. Consider an airplane flying at an angle of attack (AOA) such that the moments about the center of gravity (cg) are zero.
3. The aircraft is therefore in equilibrium at α_e and is said to be trimmed, and α_e is called the trim angle of attack.
4. Now imagine that a wind gust disturbs the airplane and changes its angle of attack to some new value α . Hence, the plane was pitched through a displacement ($\alpha - \alpha_e$)
5. Three responses are possible



Aperiodic Damped



Damped Oscillatory



Un-damped Divergent

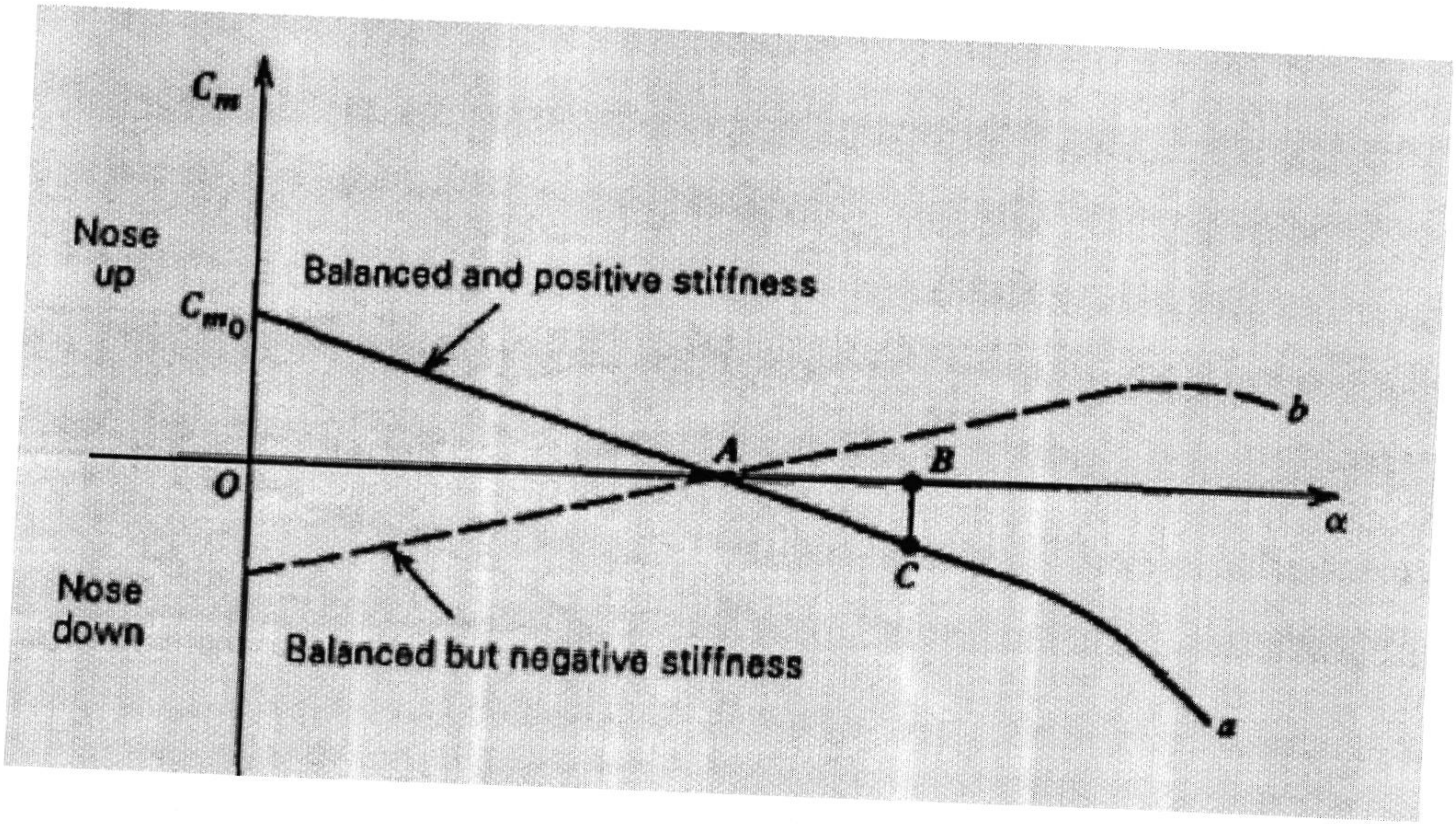
Stability

- For a successful flight :
  - Airplane must be able to achieve equilibrium flight
  - It must be manoeuvrable for wide range of velocities and altitudes
- For these, aircraft must possess aerodynamic and propulsive controls
- Stability and control characteristics of an airplane are referred to as handling characteristics

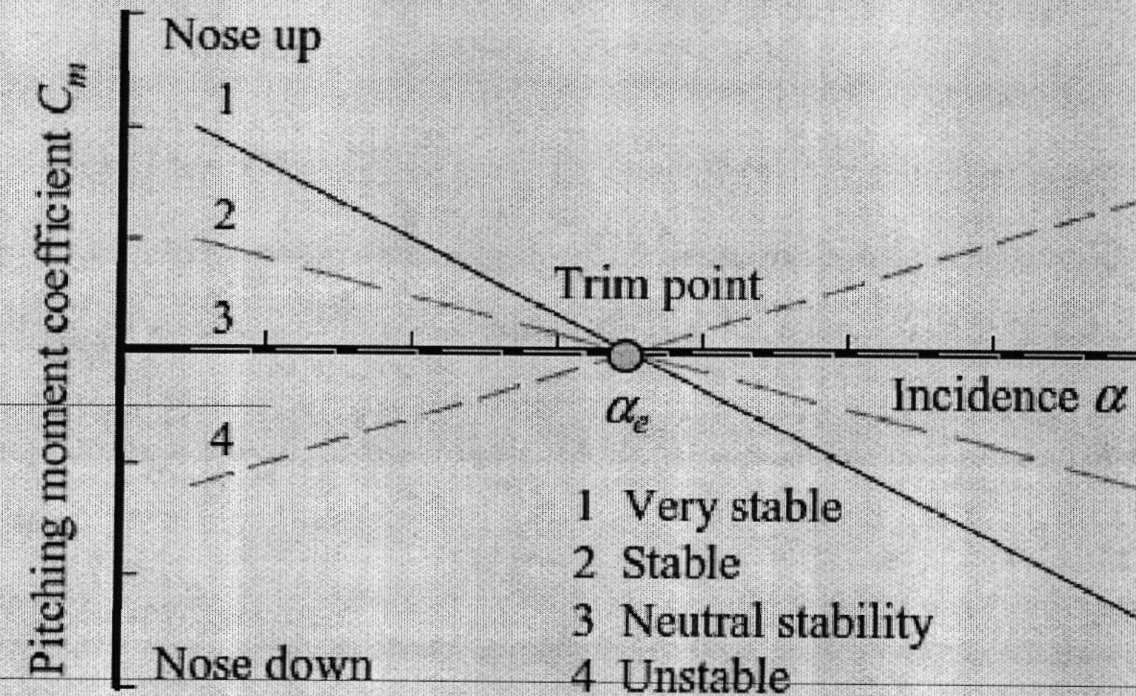
Longitudinal Stability and Control

- Wing Contribution
- Aft Tail Contribution
- Canard Configuration
- Fuselage Contribution
- Power Effects
- Elevator Effectiveness
- Elevator Trim
- Hinge Moment

Pitching Moment Vs CL

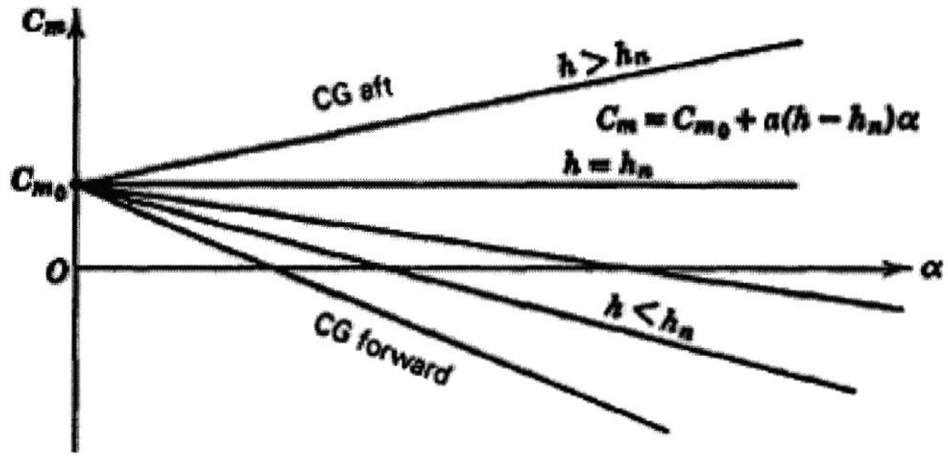


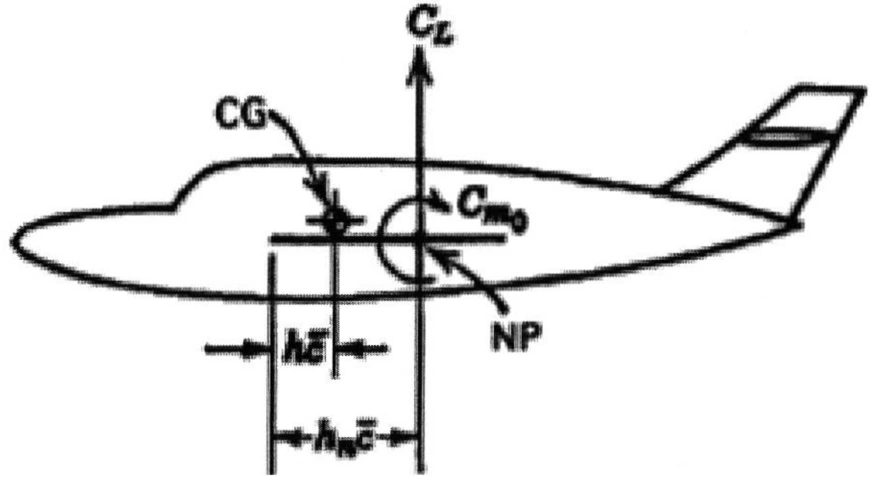
Degree of Longitudinal Stability



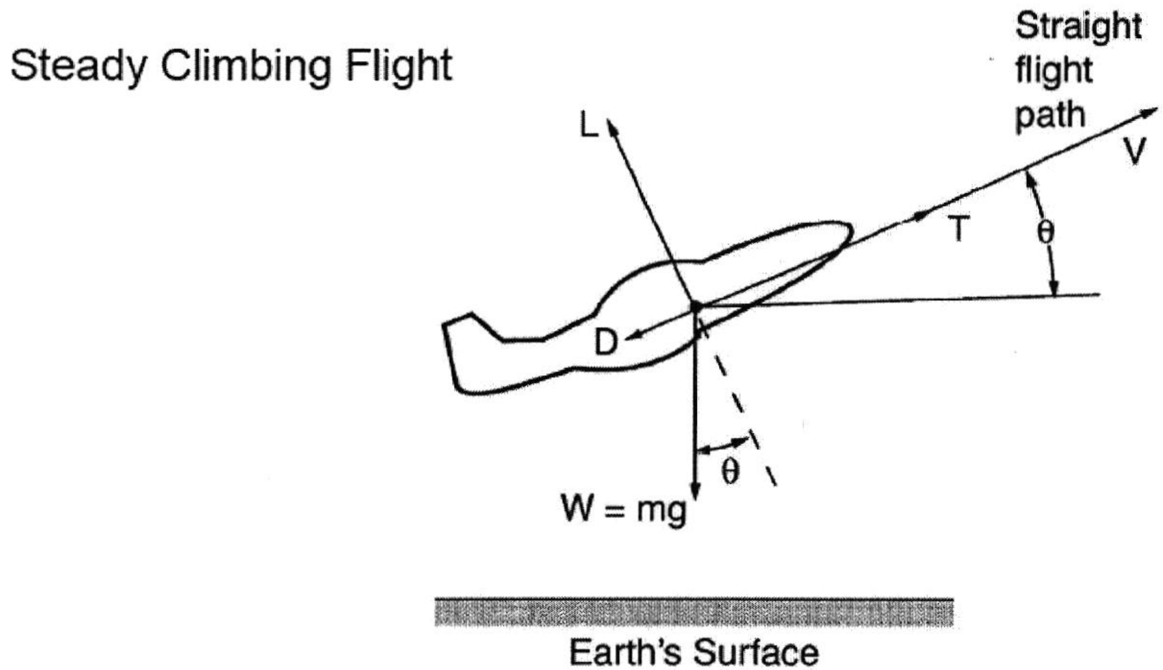
The degree of longitudinal static stability.

Effect of CG movement





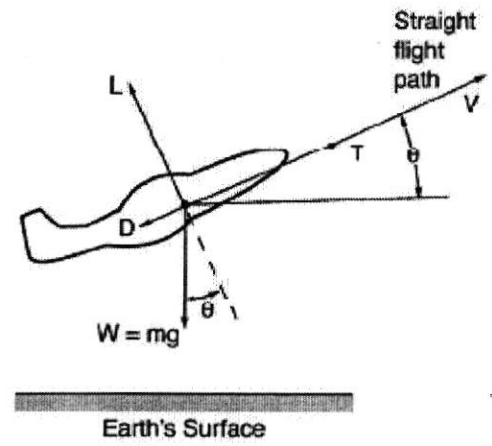
Rate of Climb (ROC)



θ - flight path angle wrt horizon (positive as shown)
Note: arrows not to scale!

Graphics source: Anderson, Aircraft Performance and Design

ROC



No acceleration (steady)

Wings level

Climbing flight at an angle θ to Earth's surface

Thrust parallel to velocity

Summing forces parallel to the flight direction:

$$T - D - W\sin\theta = 0$$

Summing forces perpendicular to the flight direction:

$$L - W\cos\theta = 0$$

Rate of Climb = ROC = $V\sin\theta$

Note that the same equations apply to steady descending flight!

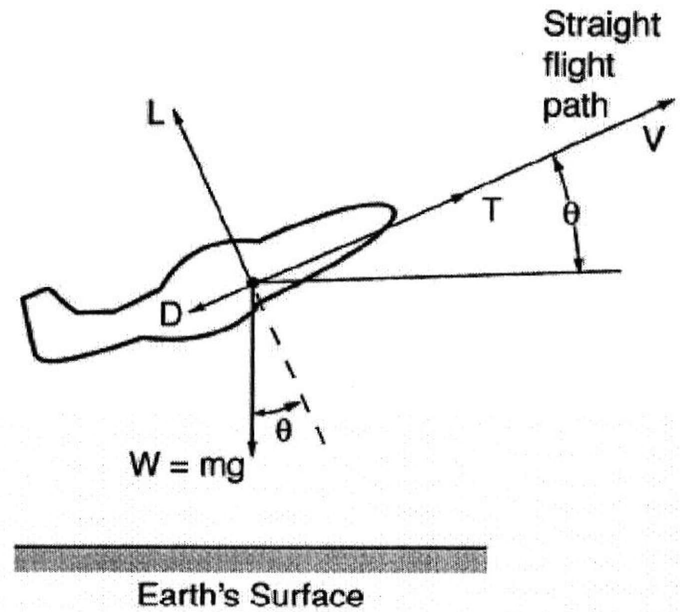
ROC

Starting with the sum of forces parallel to the flight direction:

$$T - D - W\sin\theta = 0$$

Multiply by V and re-arrange:

$$\frac{TV - DV}{W} = V\sin\theta = ROC$$



Note that:

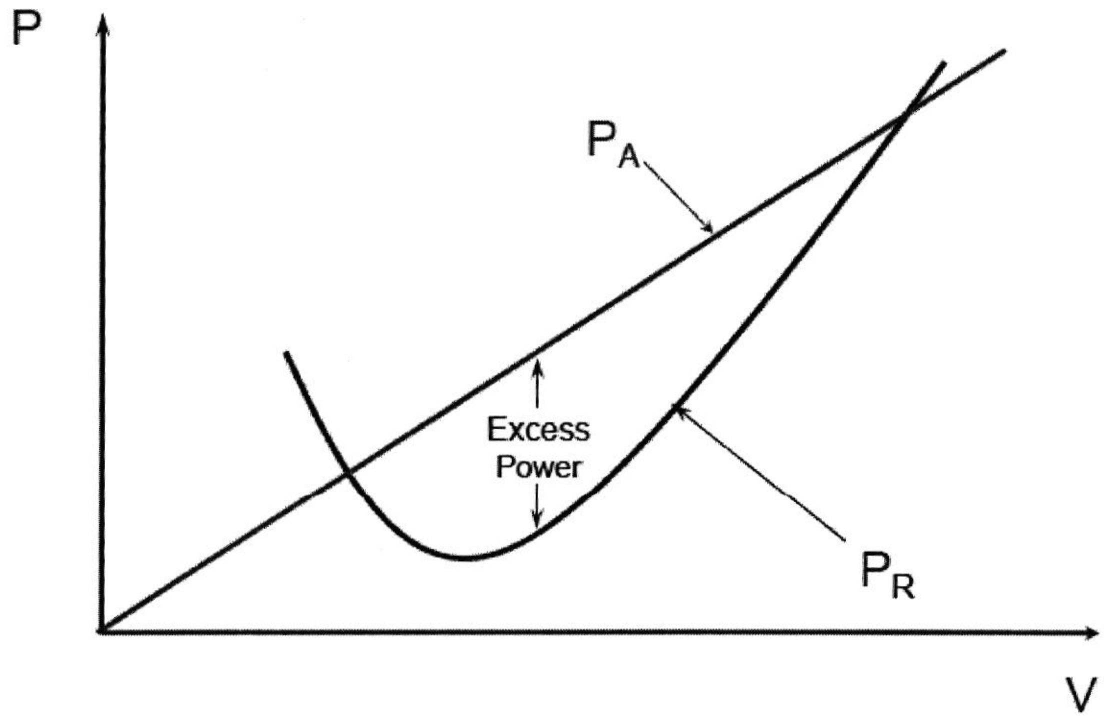
$T\,V = P_A$ = Power Available

$D\,V = P_R$ = Power Required

Thus,

$$ROC = \frac{\text{Power Available} - \text{Power Required}}{W} = \frac{\text{Excess Power}}{W}$$

ROC



$$ROC = \frac{TV - DV}{W} = \frac{P_A - P_R}{W} = \frac{\text{Power Available} - \text{Power Required}}{W} = \frac{\text{Excess Power}}{W}$$

Typical ROC numbers

Aircraft	Type	Sea level, R/C_{max}	Minimum time to climb
Mirage III	Interceptor	5.0 km/min	3.0 mt to 11 km
Mirage 2000	Interceptor	14.94 km/min	2.4 mt to 14.94 km
F-111	Fighter	10.94 km/min	N/A
F-4	Fighter	8.534 km/min	N/A
F-14	Interceptor	9.14 km/min	N/A
F-15	Fighter	15.24 km/min	N/A
F-16	Fighter	15.24 km/min	N/A

Ref : Performance Stability Dynamics and Control by Bandu Pamadi

Turn Performance

- Airplanes turn by tilting the Lift vector, to give :
  - Horizontal component, L * Sin (μ), 'μ' bank angle
  - Sharper the turn, larger the needed Lift Vector

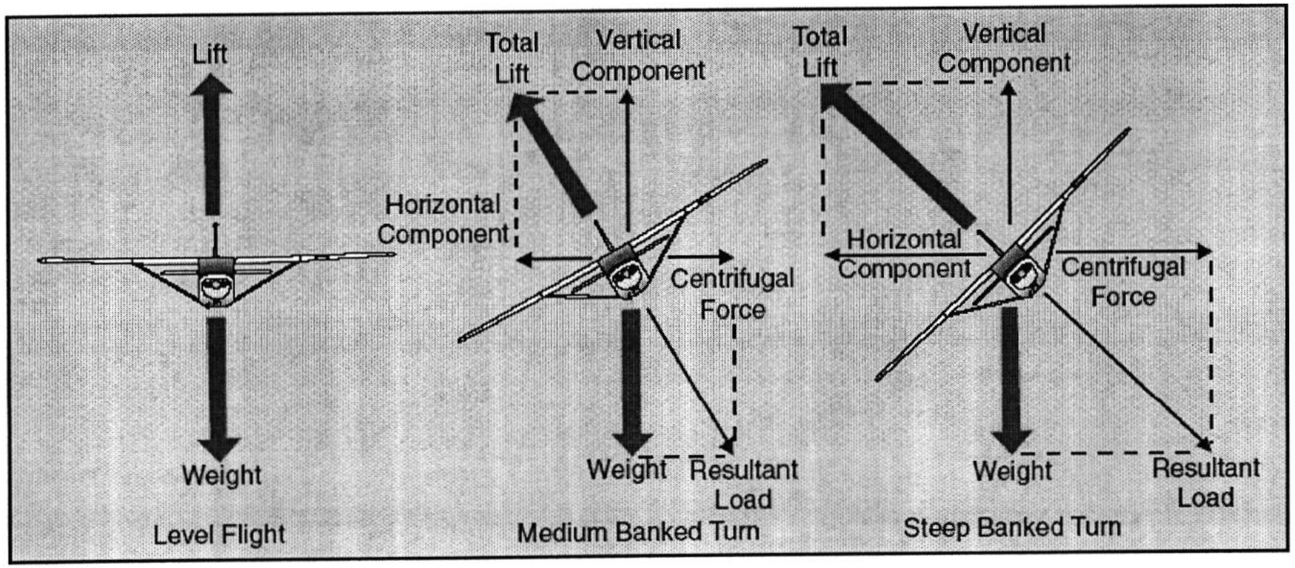


Figure 3-20. Forces during normal coordinated turn.

Turn Performance

$$T - D = 0$$

$$L\cos\mu - W = 0$$

$$L\sin\mu - \frac{WV^2}{gR} = 0$$

$$n = \frac{1}{\cos\mu}$$

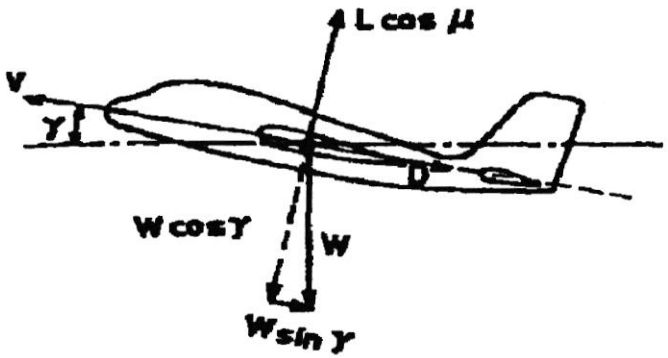
$$V = \sqrt{\frac{2nW}{\rho S C_L}}$$

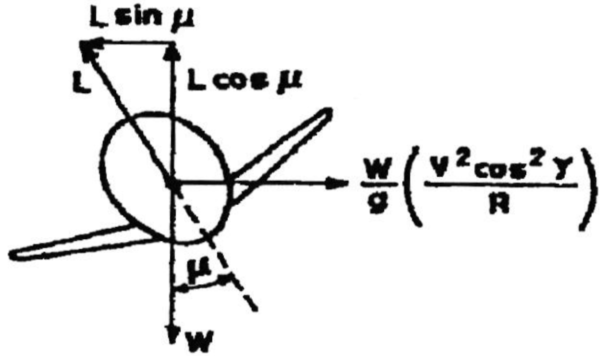
$$= \sqrt{\frac{2W}{\rho S C_L \cos\mu}}$$

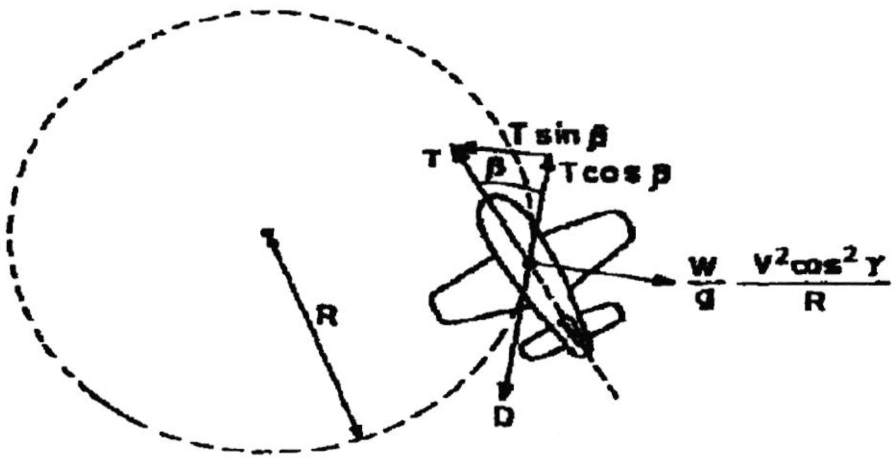
$$\tan\mu = \frac{V^2}{Rg}$$

$$R = \frac{V^2}{g\tan\mu}$$

Turn Performance







Range : How Far

Range - How far can we fly?

In this discussion we will try develop integral equations to calculate the range of an airplane during its cruise leg.

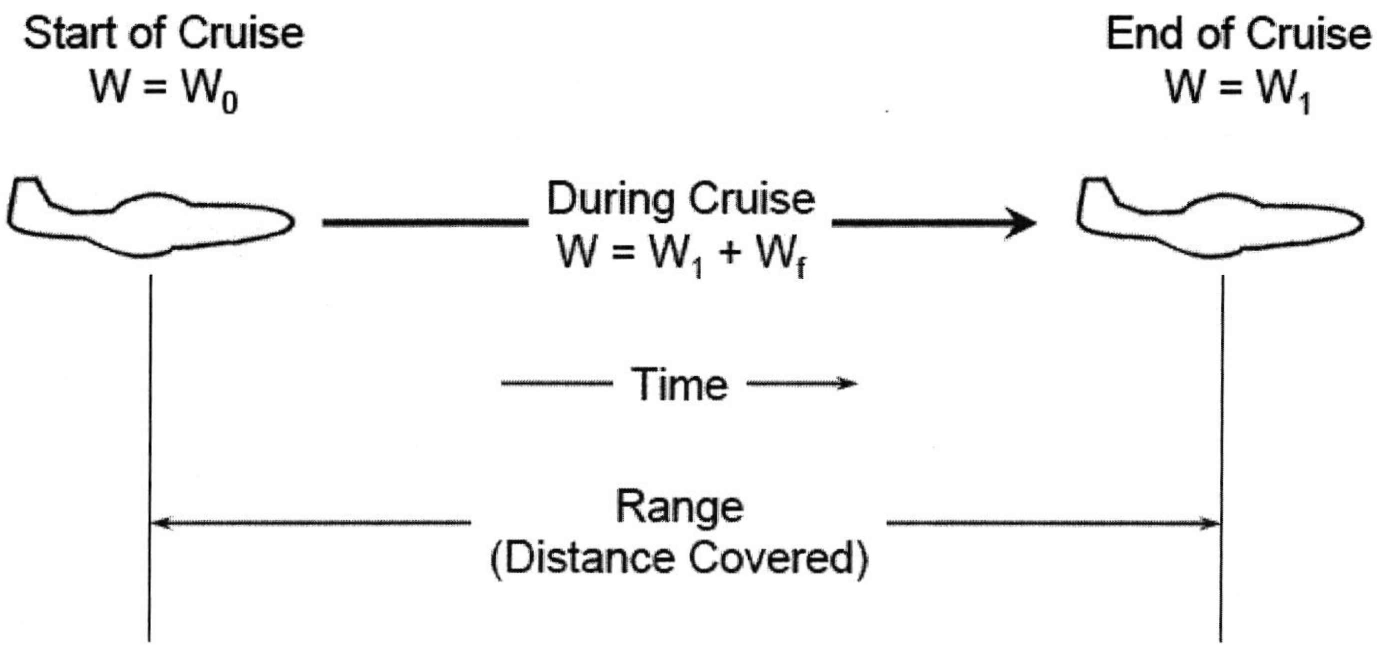
Range will be significantly affected by weight, so let us start by defining some weight quantities. Let:

- W_0 - Weight of the airplane at the start of cruise leg
- W_f - weight of fuel at a specific point in time; varies throughout the cruise leg
- W_1 - weight of the airplane at the end of the cruise leg
- W - weight of the airplane at a specific point in time; varies throughout the cruise leg

At any point during the cruise leg, then:

$$W = W_1 + W_f$$

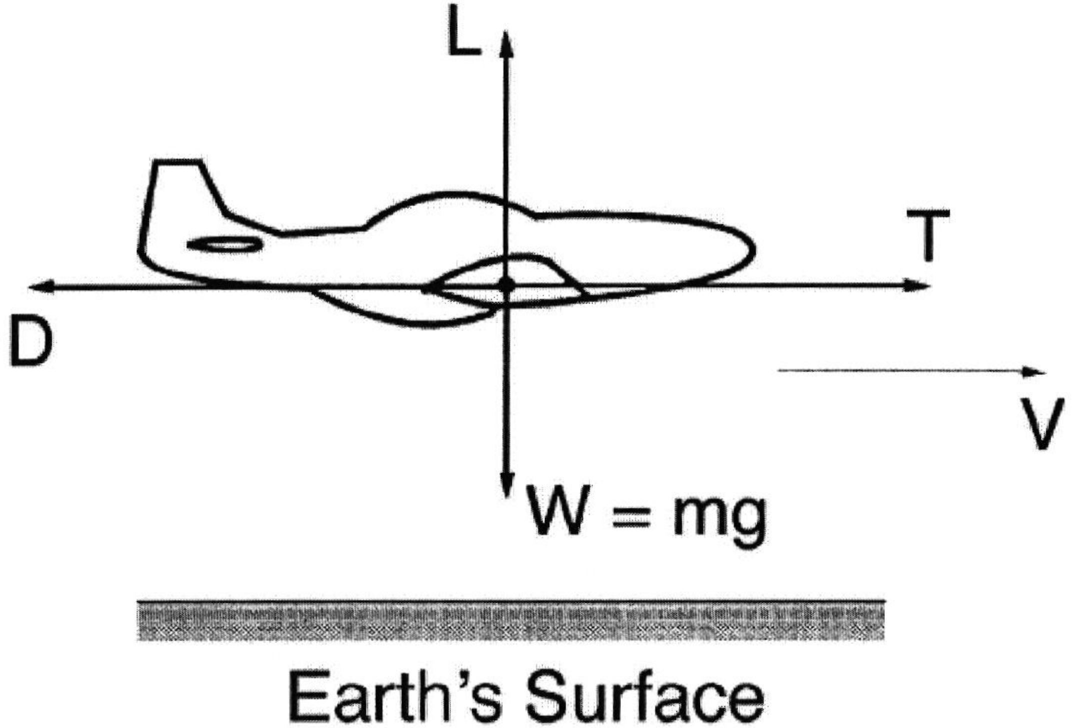
Range



Note: No assumption is being made about the flight altitude at this time - altitude during cruise __may__ or __may not__ be constant!

Range

Let us assume we are in level steady flight, and that our thrust vector is aligned with the airspeed:



$$T = D$$
$$L = W$$

Range

After a certain amount of calculus and manipulation we can write the following integral equation for the range, R, of a turbojet airplane:

$$R = \int_{W_1}^{W_0} \frac{V}{c_t} \frac{L}{D} \frac{dW}{W} = \int_{W_1}^{W_0} \frac{1}{c_t} \sqrt{\frac{2}{\rho S}} \frac{C_L^{1/2}}{C_D} \frac{dW}{\sqrt{W}}$$

Very few assumptions were made to derive this equation:

- Flight in no-wind conditions
- Steady level flight
  $L = W$
  $T = D$
- Thrust aligned with V

Range

We can make some further assumptions and that will simplify the integral and allow us to evaluate it explicitly:

- The thrust specific fuel consumption, c_t is constant
- We are flying at a constant altitude, thus ρ is constant
- The wing area, S, is constant (we hope so!)
- We are flying at a constant value of $\left(C_L^{1/2}/C_D\right)$

These assumptions allow us to move various quantities in front of the integral:

Range

$$R = \frac{1}{c_t}\sqrt{\frac{2}{\rho S}}\frac{C_L^{1/2}}{C_D}\int_{W_1}^{W_0}\frac{dW}{\sqrt{W}}$$

Now we can evaluate this integral explicitly:

$$R = \frac{2}{c_t}\sqrt{\frac{2}{\rho S}}\frac{C_L^{1/2}}{C_D}\left(W_0^{1/2} - W_1^{1/2}\right)$$

This is one version of the range equation for a turbojet airplane.

Range

$$R = \frac{2}{c_t}\sqrt{\frac{2}{\rho S}}\frac{C_L^{1/2}}{C_D}\left(W_0^{1/2} - W_1^{1/2}\right)$$

What is this equation telling us about obtaining maximum range for a turbojet airplane?

- For maximum range, fly at the value of C_L where $\left(C_L^{1/2}/C_D\right)$ is maximum.
- Fly at high altitude so that ρ is small (within limits…).
- Use an efficient engine with a low value of c_t.
- Carry lots of fuel.

Range

A similar equation can be derived for an airplane powered by a reciprocating engine/propeller combination:

$$R = \frac{\eta_{pr}}{c}\frac{C_L}{C_D}\ln\frac{W_0}{W_1}$$

Where,

η_{pr} is the propeller efficiency
c is the power specific fuel consumption

This is one of the best known equations in aeronautics. It is known as the Breguet Range Equation.

What is this equation telling us about obtaining maximum range for a reciprocating engine/propeller airplane?

Session Objectives

- Aircraft Performance:
  - Basics of performance (steady state and accelerated)
  - Performance characteristics of aircraft for (Civil – passenger, cargo, Military- fighter, bomber)
  - Range, Endurance, Rate of climb, maximum Mach number
- Stability and Control
  - Basics of stability : CG location , AC, limits
  - Longitudinal, Lateral control

Performance Basics

Speeds : Maximum and Stall, Range, and Rate of Climb

Performance

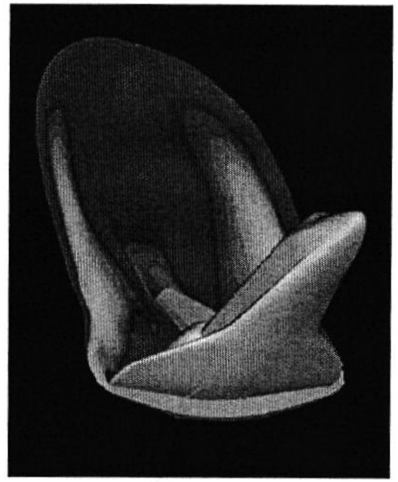
- Performance: A measure of how well a device does its job
- Airplane Performance Examples
  - Speed -> how fast/slow can it go?
  - Rate of Climb -> how fast can it go up?
  - Ceiling -> how high can it go?
  - Range -> how far can it go?
  - Endurance -> for how long can it fly?
  - Takeoff/Landing -> how much runway does it need?
  - Turning -> what is the minimum turn radius?

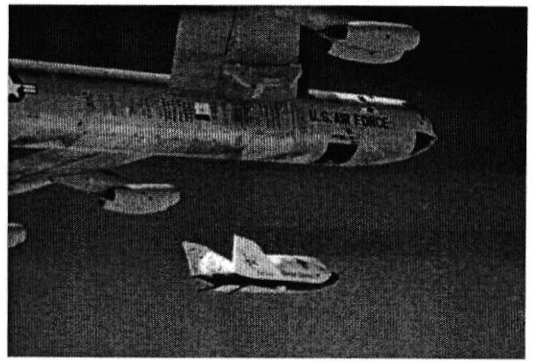
Performance

- Helicopter Performance Examples
  - Hover Capability -> how much weight can it lift vertically?
  - Speed -> how fast can it go?
  - Rate of Climb -> how fast can it go up?
  - Ceiling -> how high can it go?
  - Range -> how far can it go?
  - Endurance -> for how long can it fly?

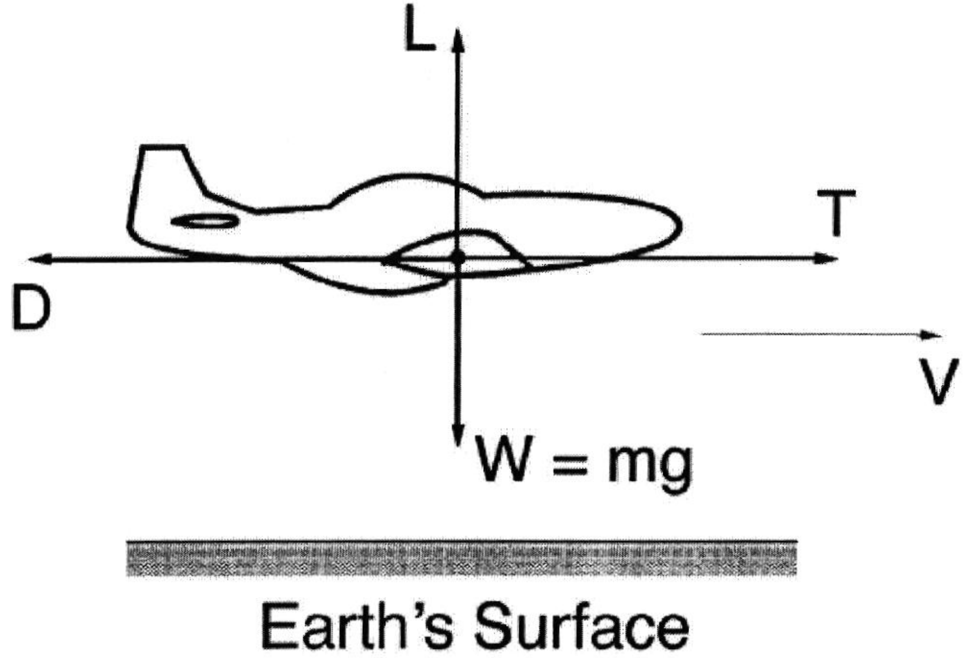
Performance

- Aircraft performance is determined by following
- Mathematical Modeling
  - Computational Fluid Dynamics
  - Classical aero/propulsive/mass analyses
- Ground Testing
  - Wind tunnel testing
  - Static engine testing
- Flight Testing





Steady level Flight



L - Lift
D - Drag
W - Weight
m - mass
g - acceleration of gravity
V - velocity, freestream airspeed (no wind)
Note: arrows not to scale!

Graphics source: Anderson, Aircraft Performance and Design

Performance

Aerodynamic Models

The lift, L, and drag, D, of the airplane can be calculated from:

$$L = \frac{1}{2}\rho V^2 S C_L \qquad D = \frac{1}{2}\rho V^2 S C_D$$

Where:

ρ is the atmospheric density
V is the airspeed
S is the wing area
C_L is the lift coefficient
C_D is the drag coefficient

Performance

Aerodynamic Models - continued…

We will model the relationship between the lift and drag of an airplane through the drag polar:

$$C_D = C_{D,0} + KC_L^2$$

Where we know the values of $C_{D,0}$ and K for our airplane.

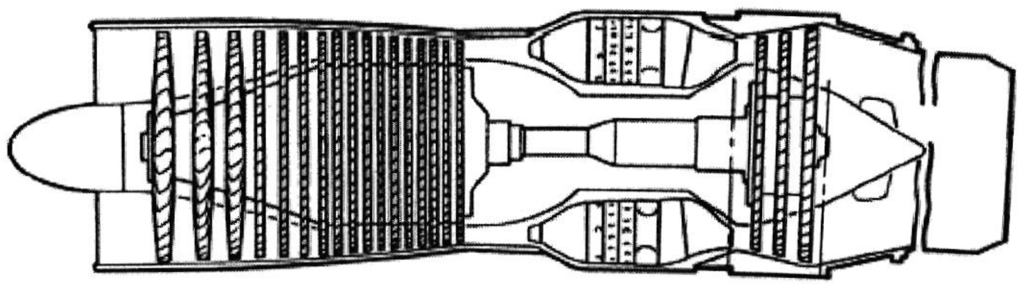
The lift coefficient, C_L, has a known maximum value:

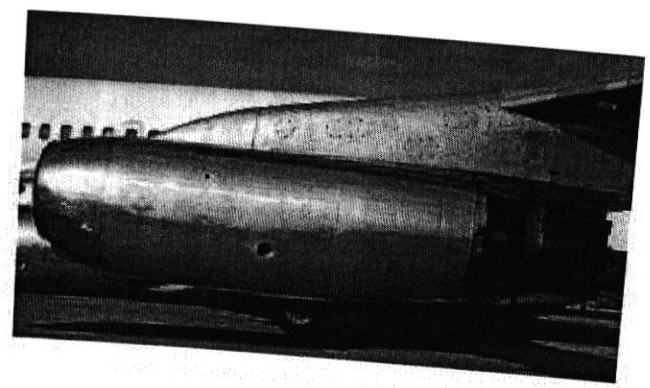
$$C_{L,Max}$$

Performance

Propulsion Models

In this introduction to performance lecture we will assume all our airplanes are using turbojet engines:





Performance

<u>Propulsion Models - continued…</u>

For a turbojet engine the maximum thrust, T_{Max}, does not change with airspeed, V, while flying at subsonic speeds.

For a turbojet engine the maximum thrust, T_{Max}, decreases with altitude as given by:

$$T_{Max} = T_{Max0}\left(\frac{\rho}{\rho_0}\right)$$

Where,

ρ_0 is the atmospheric density at sea level
T_{Max0} is the maximum thrust at sea level

Performance

Propulsion Models - continued…

How do we quantify the fuel consumption of a turbojet engine? We usually do so by calculating the thrust specific fuel consumption, c_t:

$$c_t = \text{thrust specific fuel consumption}$$

$$= \frac{(\text{weight of fuel consumed for a given time increment})}{(\text{thrust output}) \bullet (\text{time increment})}$$

$$= \frac{\dot{W}_{fuel}}{T}$$

In this lecture we will model c_t as follows:

At subsonic speeds c_t is constant. It does not vary with velocity or altitude.

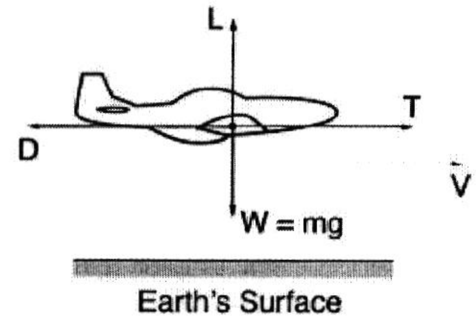
Stall Speed

By definition, lift is perpendicular to the wing and V

By definition drag is parallel to V

No acceleration (steady), dV/dt = 0

Wings level



Horizontal flight parallel to Earth's surface (level)

Usually the magnitude of L and W are greater than D and T

Summing forces parallel to the flight direction:

$$T - D = 0 \quad \text{or equivalently} \quad T = D$$

Summing forces perpendicular to the flight direction:

$$L - W = 0 \quad \text{or equivalently} \quad L = W$$

Stall Speed

Let us determine how slow we can fly in steady level flight. In other words, we want to determine the stall speed, V_{stall}.

$$L = \frac{1}{2}\rho V^2 S C_L = W$$

$$V = \sqrt{\frac{2W}{\rho S C_L}}$$

How do we minimize V for a given airplane?
By flying at $C_{L,Max}$!

$$V_{stall} = \sqrt{\frac{2W}{\rho S C_{L,Max}}}$$

Stall Speed : Example

$$V_{stall} = \sqrt{\frac{2W}{\rho S C_{L,Max}}}$$

How does the various parameters in this equation:

$$W,\ \rho,\ S,\ C_{L,Max}$$

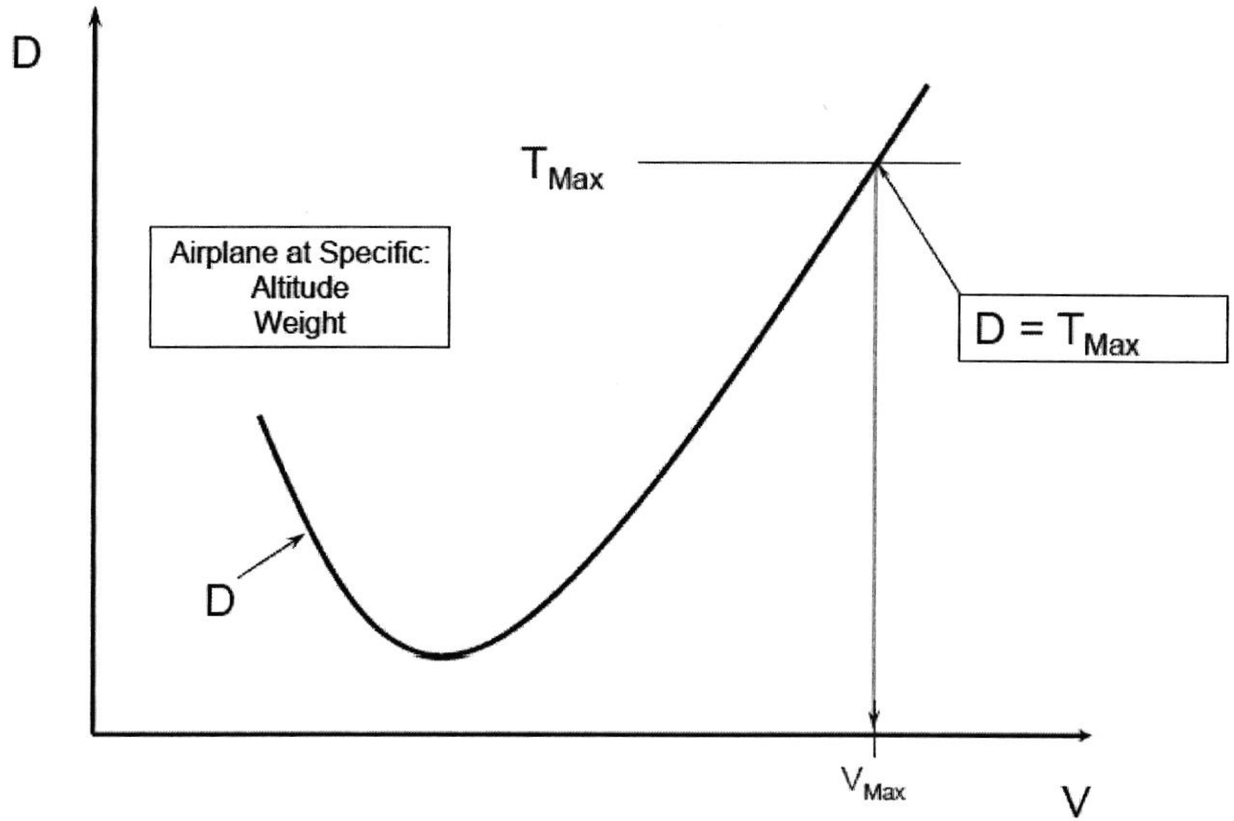
affect V_{stall}?

Numerical Example: Motorglider

$m = 300$ kg
$W = mg = 2{,}943$ N
$\rho = 1.225\ kg/m^3$ (i.e., sea level)
$S = 12.5\ m^2$
$C_{L,Max} = 1.5$

$V_{stall} = 16$ m/s

V_{max} : Maximum Speed



V_{max} : Maximum Speed

To determine the maximum speed of a turbojet airplane we start with the equation of motion:

$$T = D$$

But we agreed to model the thrust as:

$$T = T_{Max} = T_{Max0}\left(\frac{\rho}{\rho_0}\right)$$

and determine drag from:

$$D = \frac{1}{2}\rho V^2 S C_D$$

Substituting these equations into the first one gives us:

$$T_{Max0}\left(\frac{\rho}{\rho_0}\right) = \frac{1}{2}\rho V^2 S C_D$$

V_{max} : Maximum Speed

$$C_D = C_{D,0} + K\frac{4W^2}{(\rho V^2 S)^2}$$

Which we can then plug in onto our equation relating thrust and drag:

$$T_{Max0}\left(\frac{\rho}{\rho_0}\right) = \frac{1}{2}\rho V^2 S C_D$$

to get, after some rearranging:

$$T_{Max0}\left(\frac{\rho}{\rho_0}\right) = \frac{1}{2}\rho V^2 S C_{D.0} + \frac{2KW^2}{\rho V^2 S}$$

Multiplying both sides of this equation by V^2 gives us:

V_{max} : Maximum Speed

$$T_{Max0}\left(\frac{\rho}{\rho_0}\right)V^2 = \frac{1}{2}\rho V^4 S C_{D.0} + \frac{2KW^2}{\rho S}$$

Which, after some rearranging gives us:

$$\left[\frac{1}{2}\rho S C_{D.0}\right]V^4 - \left[T_{Max0}\left(\frac{\rho}{\rho_0}\right)\right]V^2 + \frac{2KW^2}{\rho S} = 0$$

Notice that this is simply a quadratic equation in V^2 of the form:

$$a\left(V^2\right)^2 + bV^2 + c = 0$$

Where,

$$a = \left[\frac{1}{2}\rho S C_{D.0}\right] \qquad b = \left[-T_{Max0}\left(\frac{\rho}{\rho_0}\right)\right] \qquad c = \left[\frac{2KW^2}{\rho S}\right]$$

V_{max} : Maximum Speed

This quadratic equation has a solution of the form:

$$V^2 = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$V = \sqrt{\frac{T_{Max0}\left(\frac{\rho}{\rho_0}\right) \pm \sqrt{T_{Max0}^2\left(\frac{\rho}{\rho_0}\right)^2 - 4C_{D,0}KW^2}}{\rho S C_{D,0}}}$$

Finally, we are interested in the maximum speed, V_{Max}, so we pick the positive root in the above equation to yield...

V_{max} : Maximum Speed

$$V_{Max} = \sqrt{\frac{T_{Max0}\left(\frac{\rho}{\rho_0}\right) + \sqrt{T_{Max0}^2\left(\frac{\rho}{\rho_0}\right)^2 - 4C_{D,0}KW^2}}{\rho S C_{D,0}}}$$

Numerical Example: Motorglider Powered by a Turbojet (Wow!)

$m = 300$ kg
$W = mg = 2{,}943$ N
$\rho = 0.6601$ kg/m^3 (i.e., 6,000 m altitude)
$\rho_0 = 1.225$ kg/m^3 (i.e., sea level)
$S = 12.5$ m^2
$C_{D,0} = 0.015$
$K = 0.020$
$T_{Max0} = 500$ N

$V_{Max} = 64.7$ m/s