Aerodynamics: Some Introductory Thoughts

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Some Historical Examples

- *Douglas DC-3*
- 1930's aircraft
- Low-speed subsonic
  - Aircraft would not have existed without knowledge of low-speed aerodynamics

Some Historical Examples

- *Boeing 707*
- 1950's aircraft
- High-speed subsonic
  - A revolution in air travel
  - Subsonic aerodynamics

Some Historical Examples

- *Bell X-1*
- 1950’s aircraft
- First transonic aircraft
    - Transonic aerodynamics

Some Historical Examples

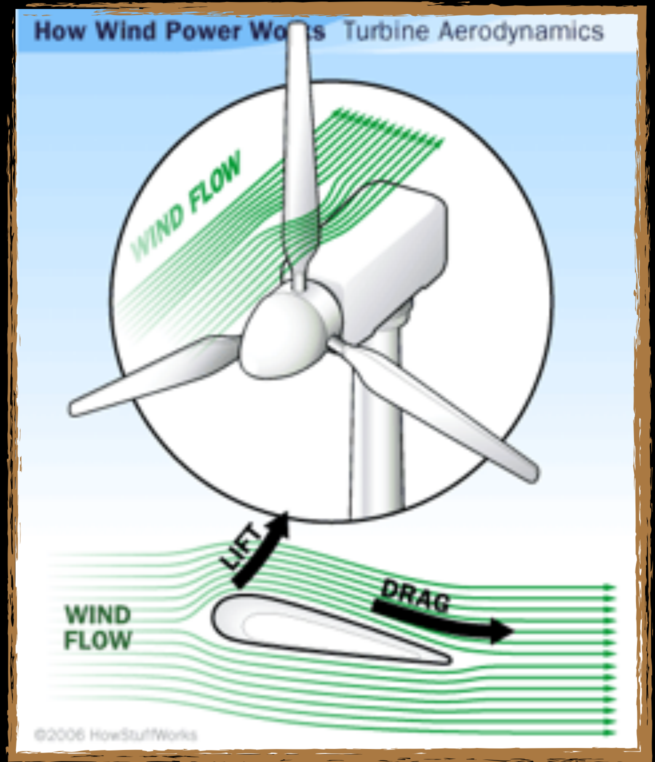
- *Lockheed F-104*
- 1950's aircraft
- First Supersonic aircraft

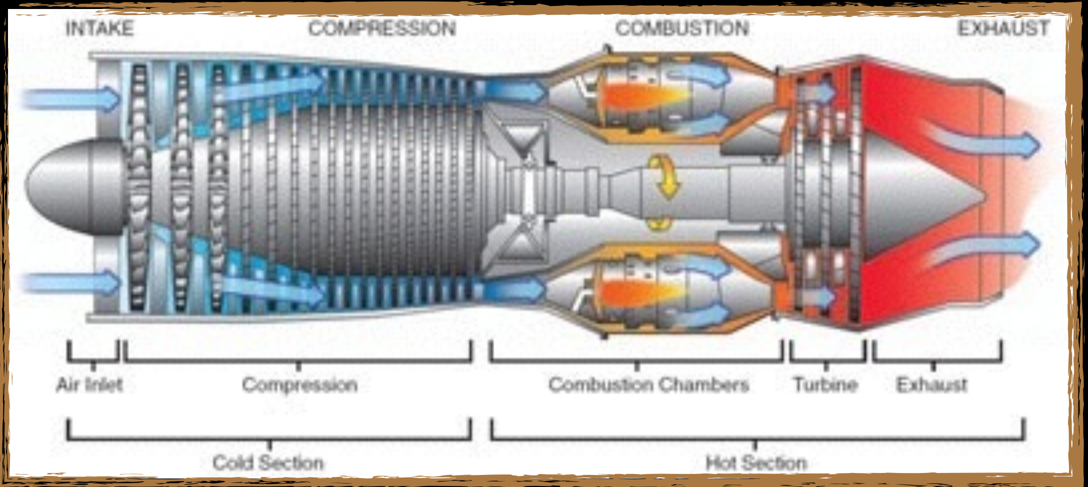
Some Historical Examples

- *Lockheed F-22 Raptor*
- Modern aircraft, supersonic

- *Lockheed F-35B VTOL*
- Modern aircraft, supersonic

Other Examples of Aerodynamics

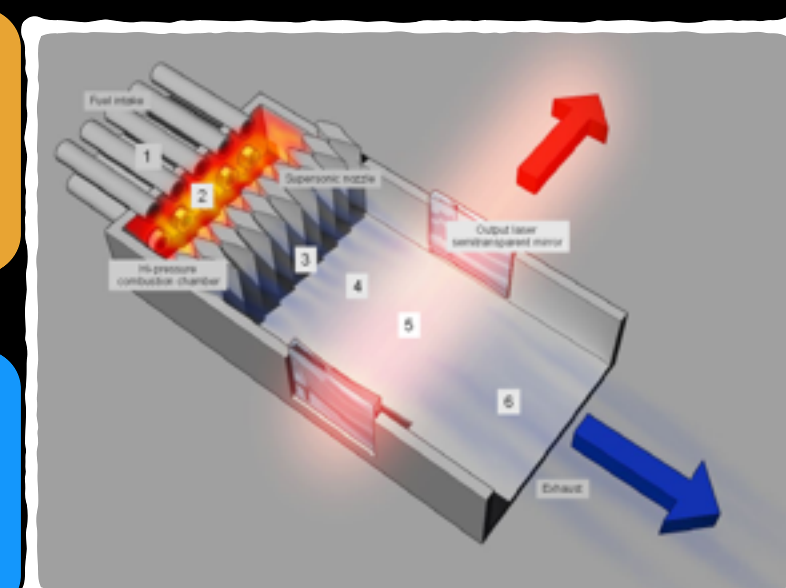




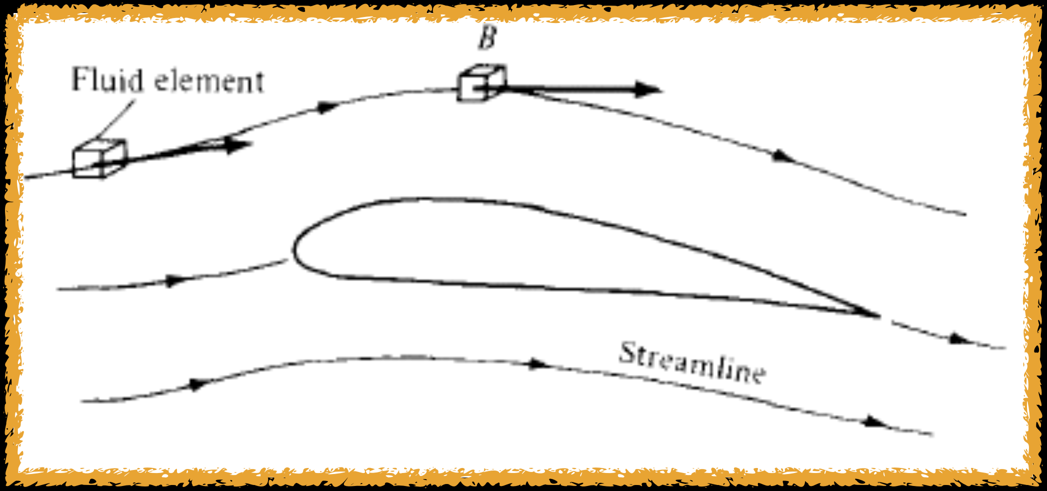
Classification and Objectives

Fluid dynamics

- Hydrodynamics
- Gas Dynamics
- Aerodynamics
  - External Aerodynamics — Forces and Moments
  - Internal Aerodynamics — Thrust, flowrate, etc.



Fundamental Aerodynamic Variables

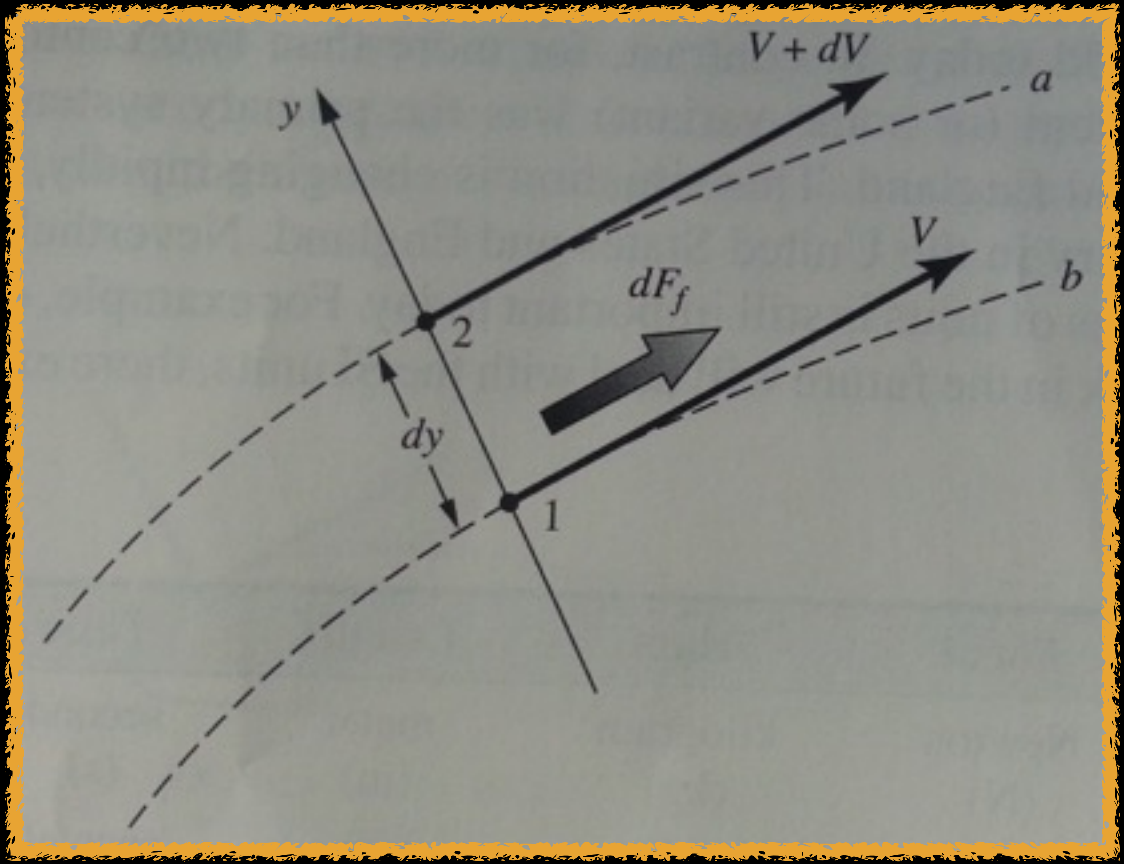


$$p = lim\left(\frac{dF}{dA}\right); dA \rightarrow 0$$

$$\rho = lim\left(\frac{dm}{dv}\right); dv \rightarrow 0$$

$$T = \frac{2}{3k}KE$$

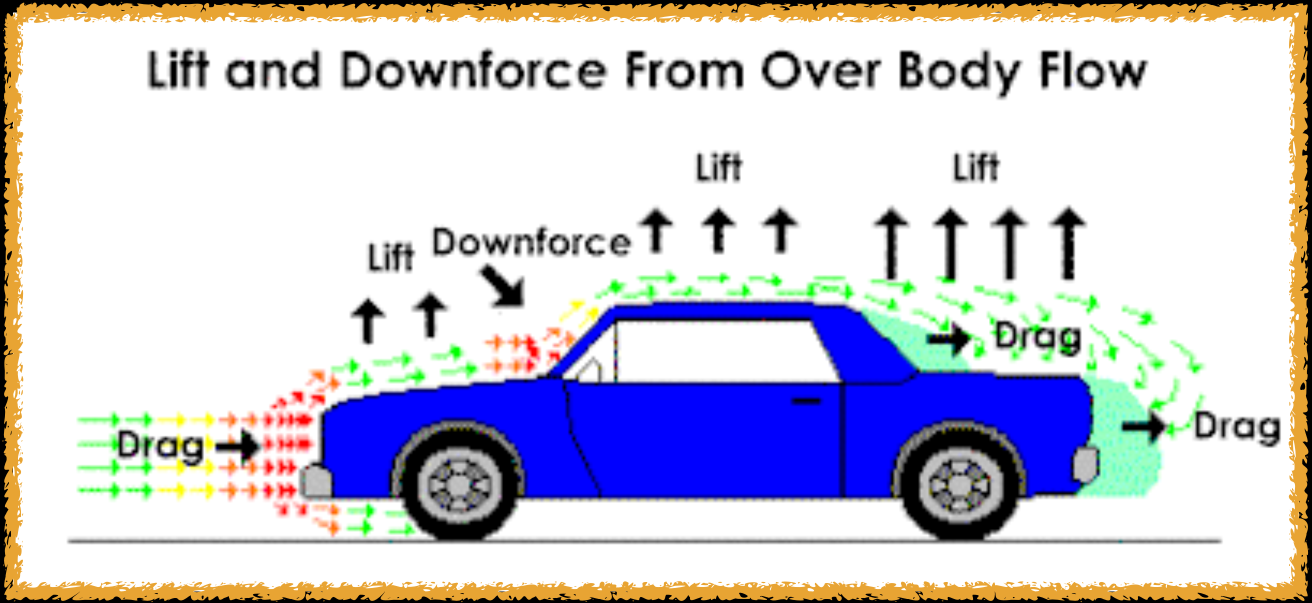
Fundamental Aerodynamic Variables



$$\tau = lim\left(\frac{dF_f}{dA}\right); dA \to 0$$

$$\tau = \mu \frac{dV}{dy}$$

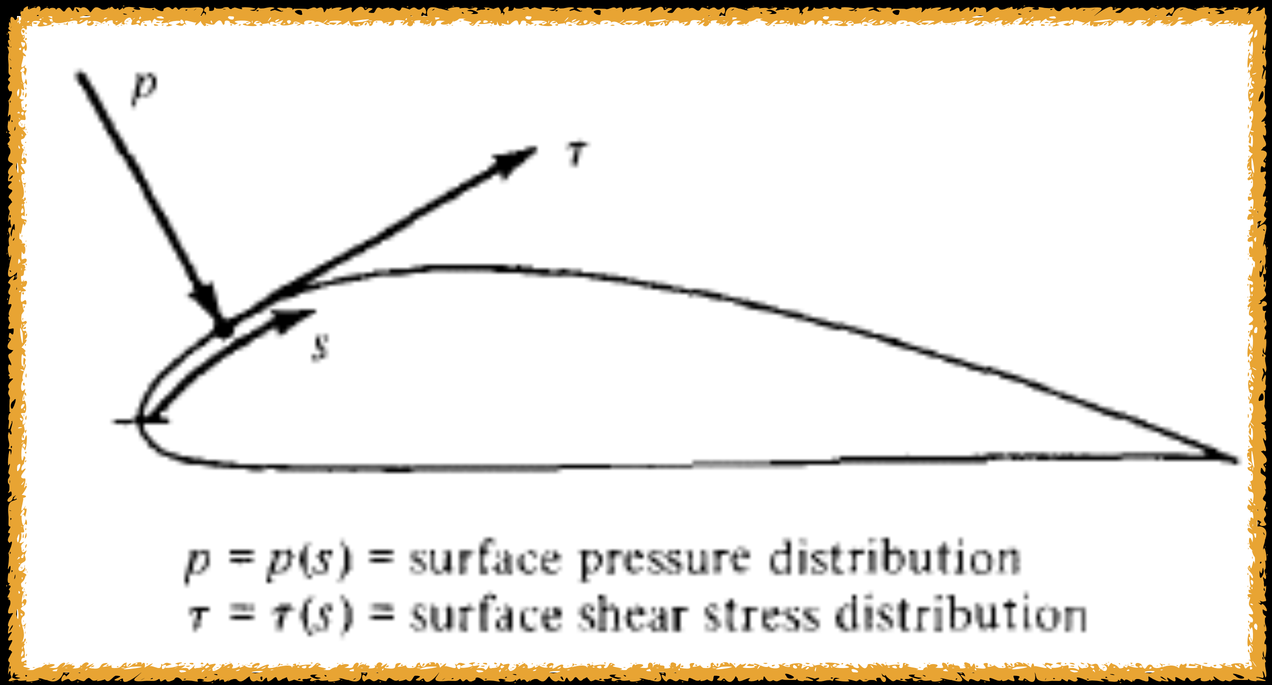
Aerodynamic Forces and Moments



- *Generation of aerodynamic forces on a 747 may seem very complex: wings, fuselage, engine nacelles, tail, etc.*
- Aerodynamic forces on an automobile on a highway: complex interaction of the body, air and ground.

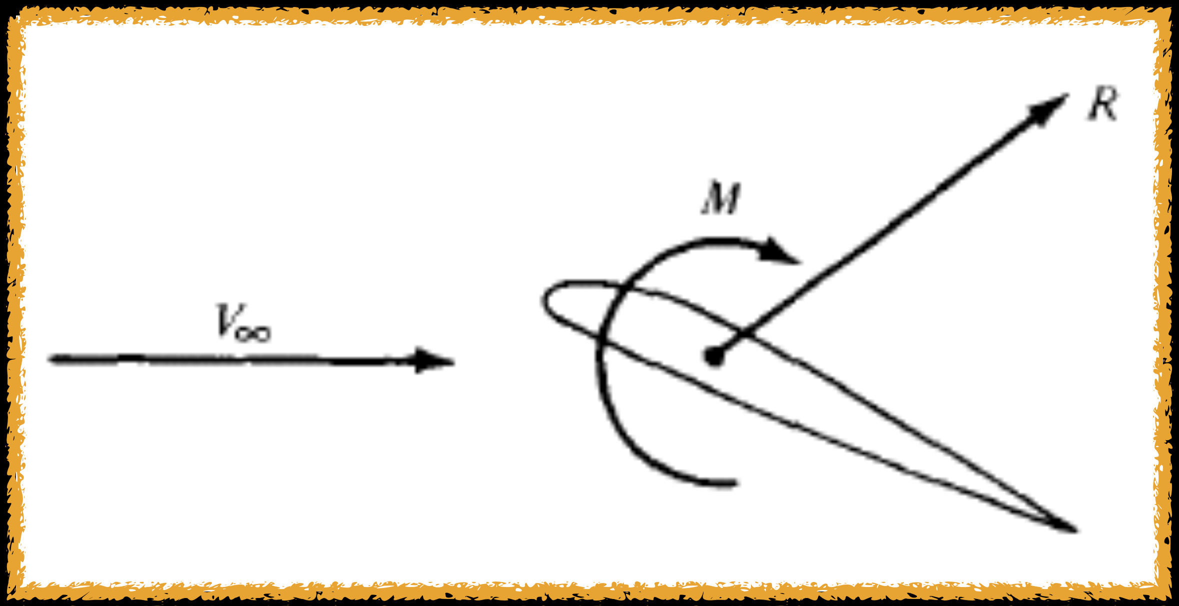
Two basic sources: ***Pressure & shear stress distribution***

Aerodynamic Forces and Moments



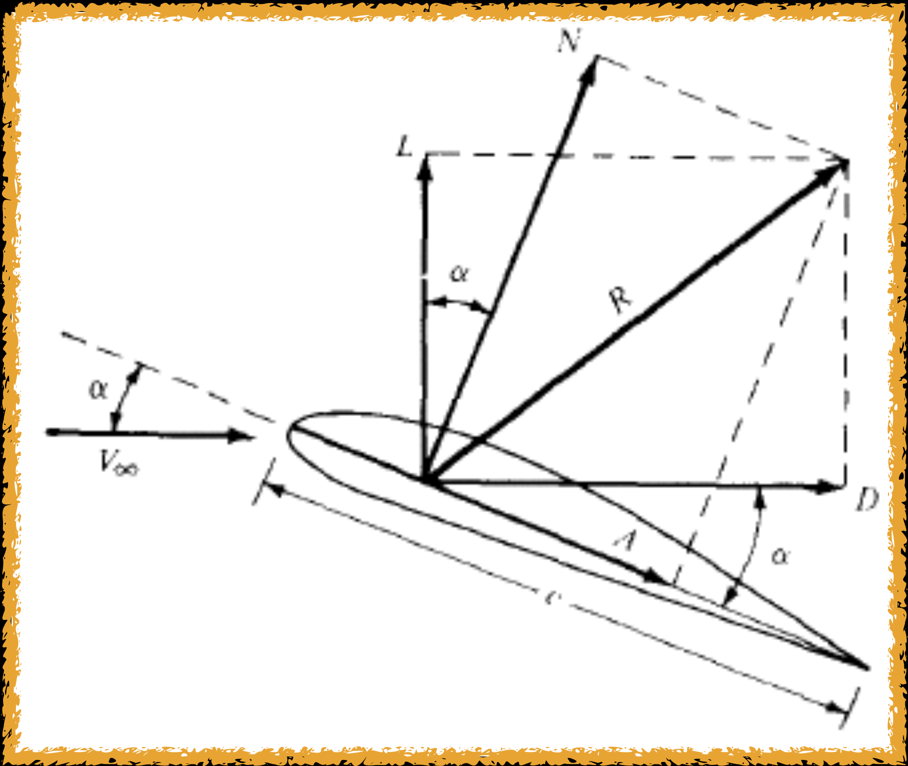
- *Only mechanisms nature has for communicating a force to body is through pressure and shear stress distributions.*
- Pressure acts normal to the surface; Shear stress acts tangential to the surface.

Aerodynamic Forces and Moments



- The net effect of pressure and shear stress distributions integrated over the complete body surface results in: ***R* & *M***
- ***R***: Aerodynamic force; ***M***: moment on the body

Aerodynamic Forces and Moments

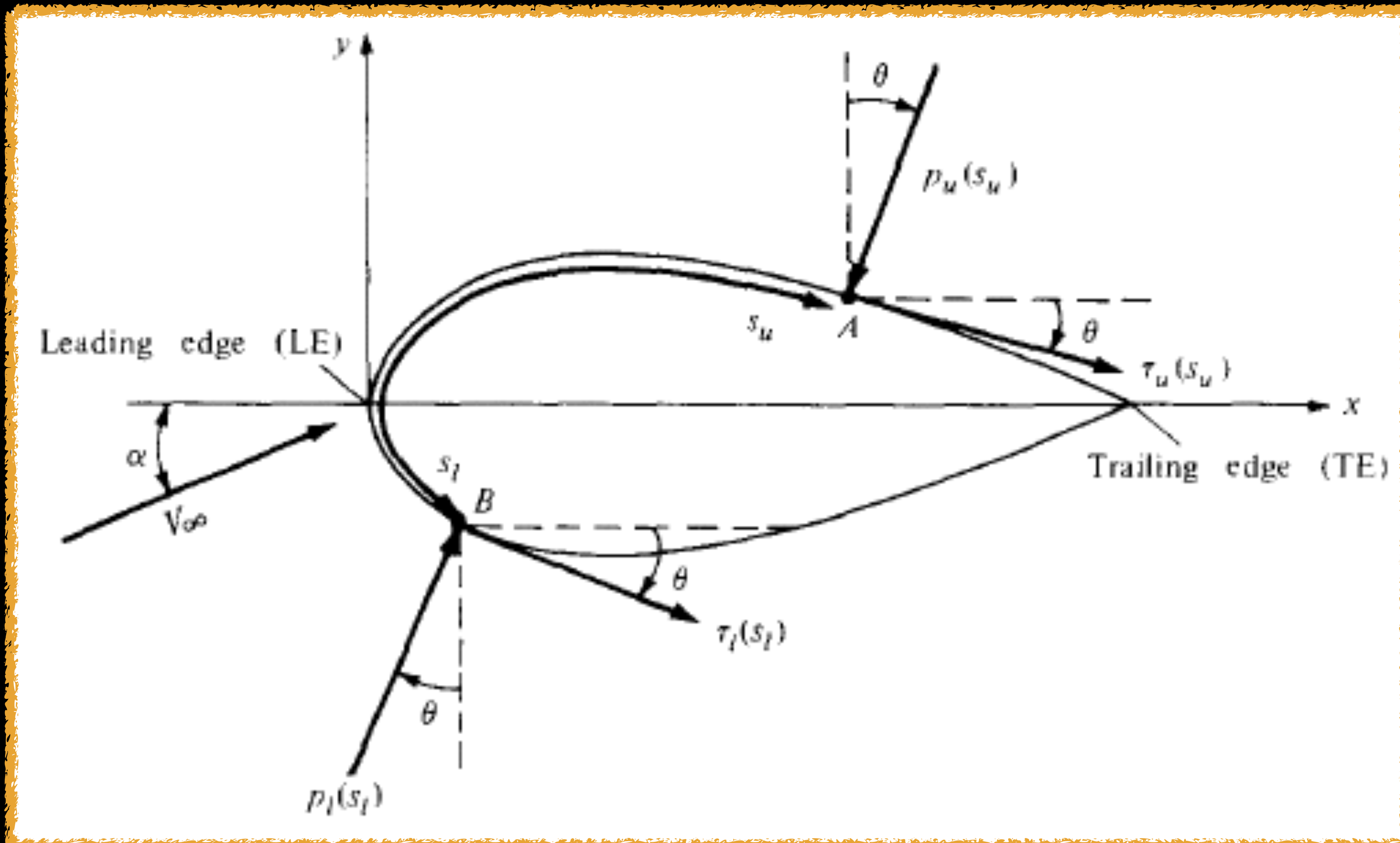


- ***R*** can be split into two components
- ***L***: ***Lift*** - component of *R* normal to V_{inf}
- ***D***: ***Drag*** - component of *R* parallel to V_{inf}
- *Chord c*: linear distance from LE to TE
- ***N***: ***Normal force*** - component of *R* normal to ***c***
- ***A***: ***Axial force*** - component of *R* parallel to ***c***
- α - ***angle of attack***

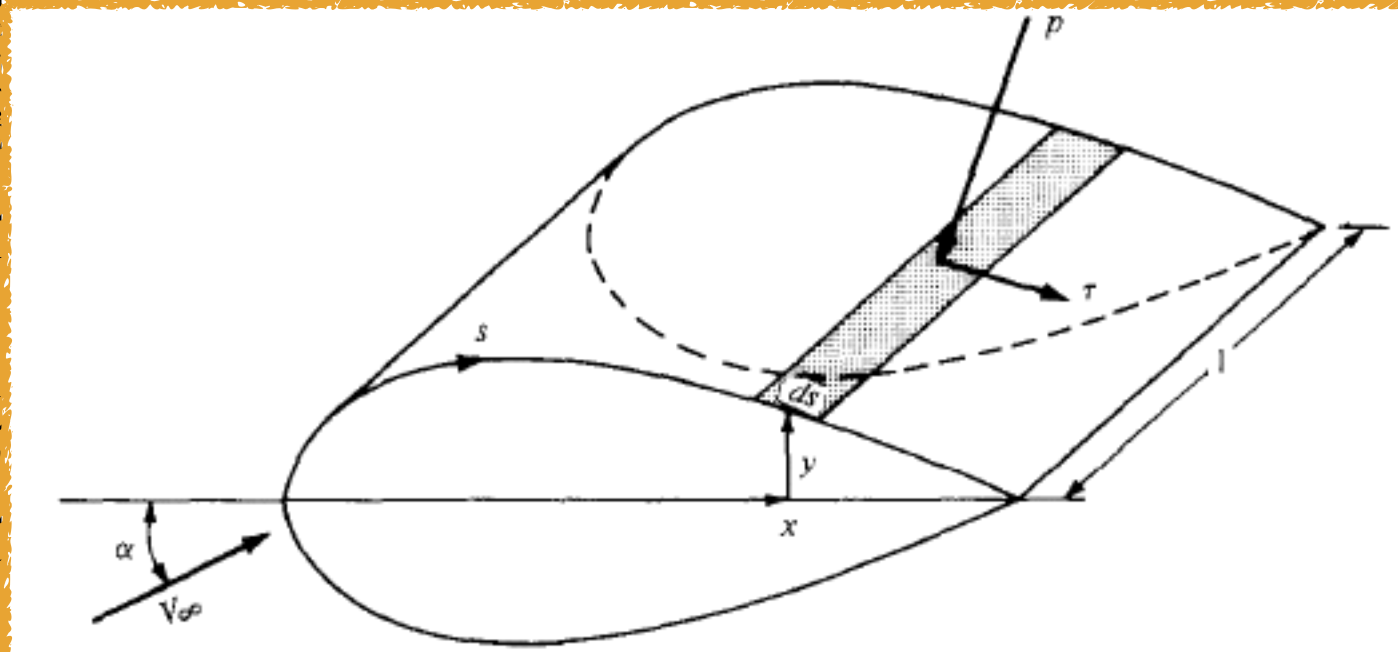
$$L = N\cos(\alpha) - A\sin(\alpha)$$

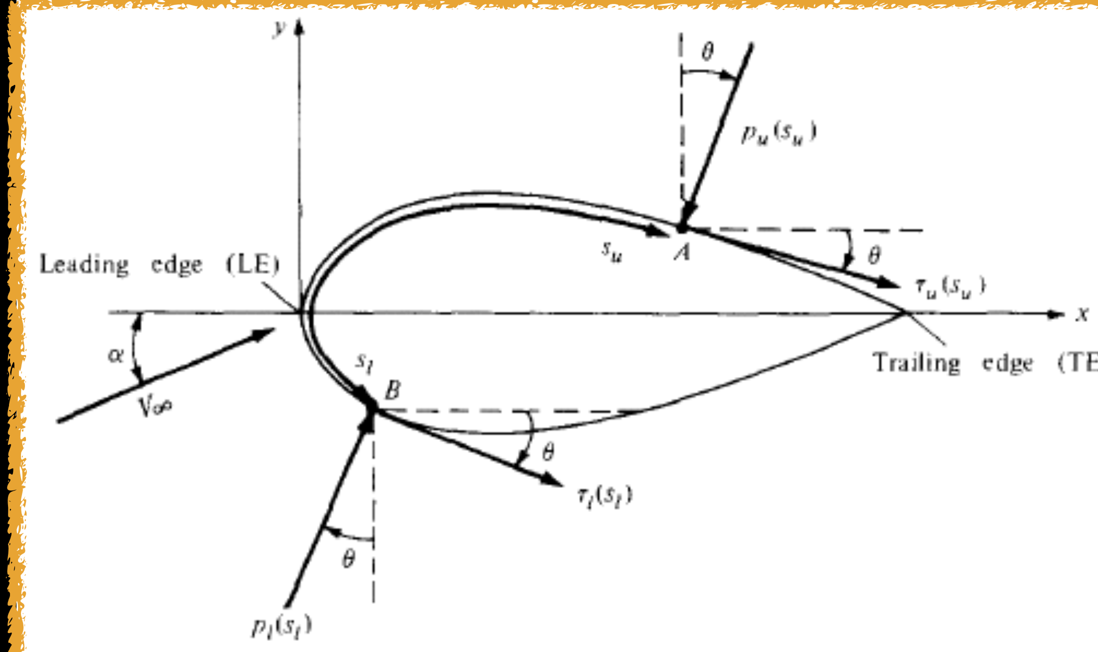
$$D = N\sin(\alpha) + A\cos(\alpha)$$

Nomenclature for a 2D Body Surface



Aerodynamic Forces





$$dN'_u = -p_u ds_u cos(\theta) - \tau_u ds_u sin(\theta)$$

$$dA'_u = -p_u ds_u sin(\theta) + \tau_u ds_u cos(\theta)$$

$$dN'_l = p_l ds_l cos(\theta) - \tau_l ds_l sin(\theta)$$

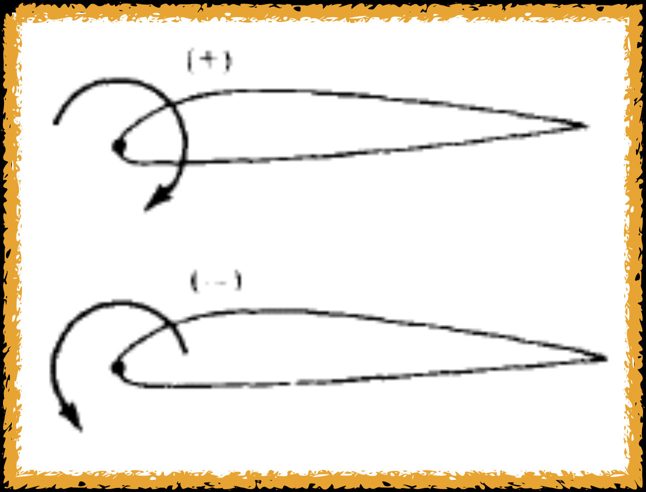
$$dA'_l = p_l ds_l sin(\theta) + \tau_l ds_l cos(\theta)$$

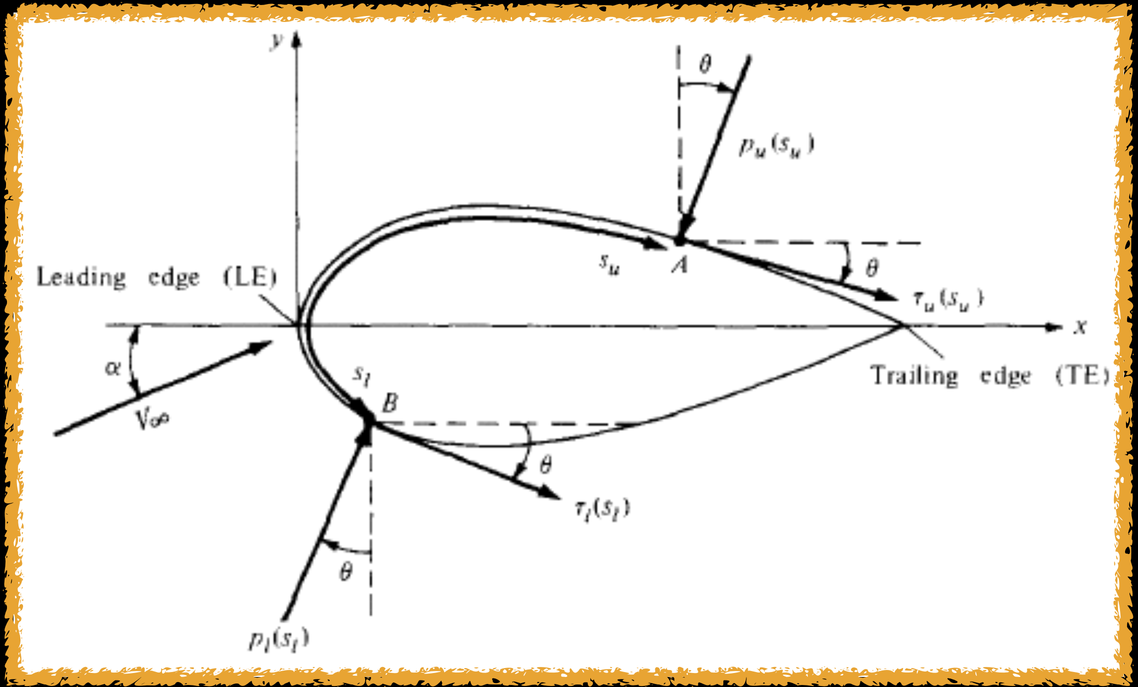
primes denote forces per unit span

$$N' = -\int_{LE}^{TE} dN'_u ds_u + \int_{LE}^{TE} dN'_l ds_l$$

$$A' = \int_{LE}^{TE} dA'_u ds_u + \int_{LE}^{TE} dA'_l ds_l$$

Aerodynamic Moments





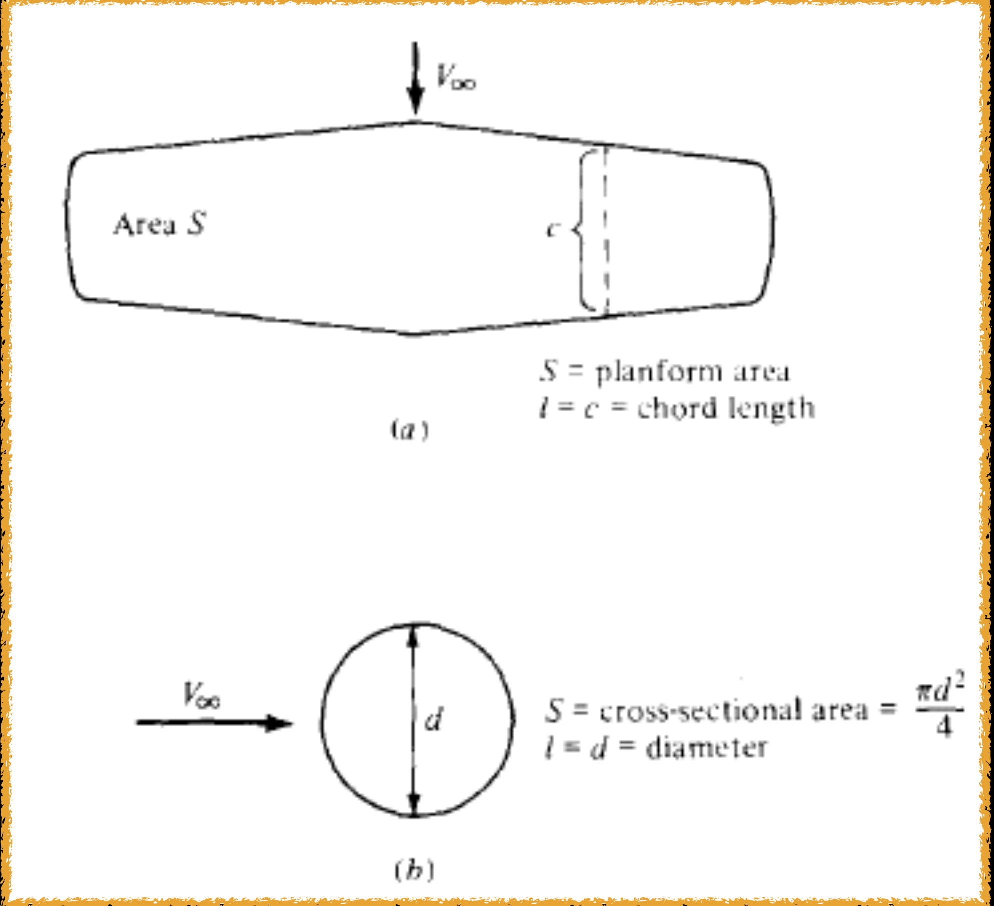
$$dM'_u = (p_u cos(\theta) + \tau_u sin(\theta))x ds_u + (-p_u sin(\theta) + \tau_u cos(\theta))y ds_u$$

$$dM'_l = (-p_l cos(\theta) + \tau_l sin(\theta))x ds_l + (p_l sin(\theta) + \tau_l cos(\theta))y ds_l$$

$$M'_{LE} = \int_{LE}^{TE} [dM'_u + dM'_l]$$

Sources of aerodynamic lift, drag and moments: *Pressure & shear stress distributions integrated over the body.*

Dimensionless Force and Moments



Dynamic pressure: $q_\infty \equiv \frac{1}{2}\rho_\infty V_\infty^2$

Lift coefficient: $C_L \equiv \dfrac{L}{q_\infty S}$

Drag coefficient: $C_D \equiv \dfrac{D}{q_\infty S}$

Normal force coefficient: $C_N \equiv \dfrac{N}{q_\infty S}$

Axial force coefficient: $C_A \equiv \dfrac{A}{q_\infty S}$

Moment coefficient: $C_M \equiv \dfrac{M}{q_\infty S l}$

For 2D bodies, forces and moments per unit span are:

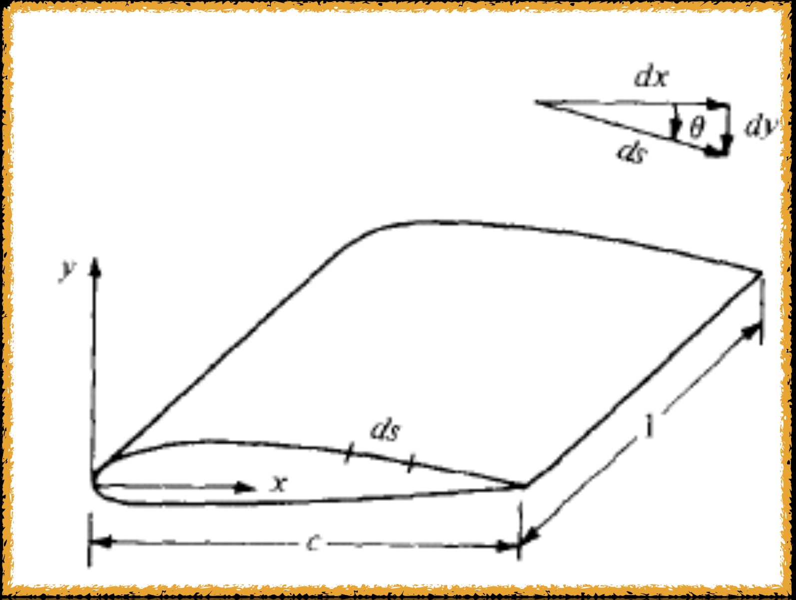
$$c_l \equiv \frac{L'}{q_\infty c} \qquad c_d \equiv \frac{D'}{q_\infty c} \qquad c_m \equiv \frac{M'}{q_\infty c^2}$$

Pressure coefficient: $C_p \equiv \dfrac{p - p_\infty}{q_\infty}$

Skin friction coefficient: $c_f \equiv \dfrac{\tau}{q_\infty}$

where p_∞ is the freestream pressure.

Dimensionless Force and Moments



$$dx = ds(cos\theta)$$

$$dy = -ds(sin\theta)$$

S = (unit span)c

Substituting into equations for N', A' and M':

$$c_n = \frac{1}{c}\left[\int_0^c (C_{p,l} - C_{p,u})\,dx + \int_0^c \left(c_{f,u}\frac{dy_u}{dx} + c_{f,l}\frac{dy_l}{dx}\right)dx\right]$$

$$c_a = \frac{1}{c}\left[\int_0^c (C_{f,u} + C_{f,l})\,dx + \int_0^c \left(c_{p,u}\frac{dy_u}{dx} - c_{p,l}\frac{dy_l}{dx}\right)dx\right]$$

Dimensionless Force and Moments

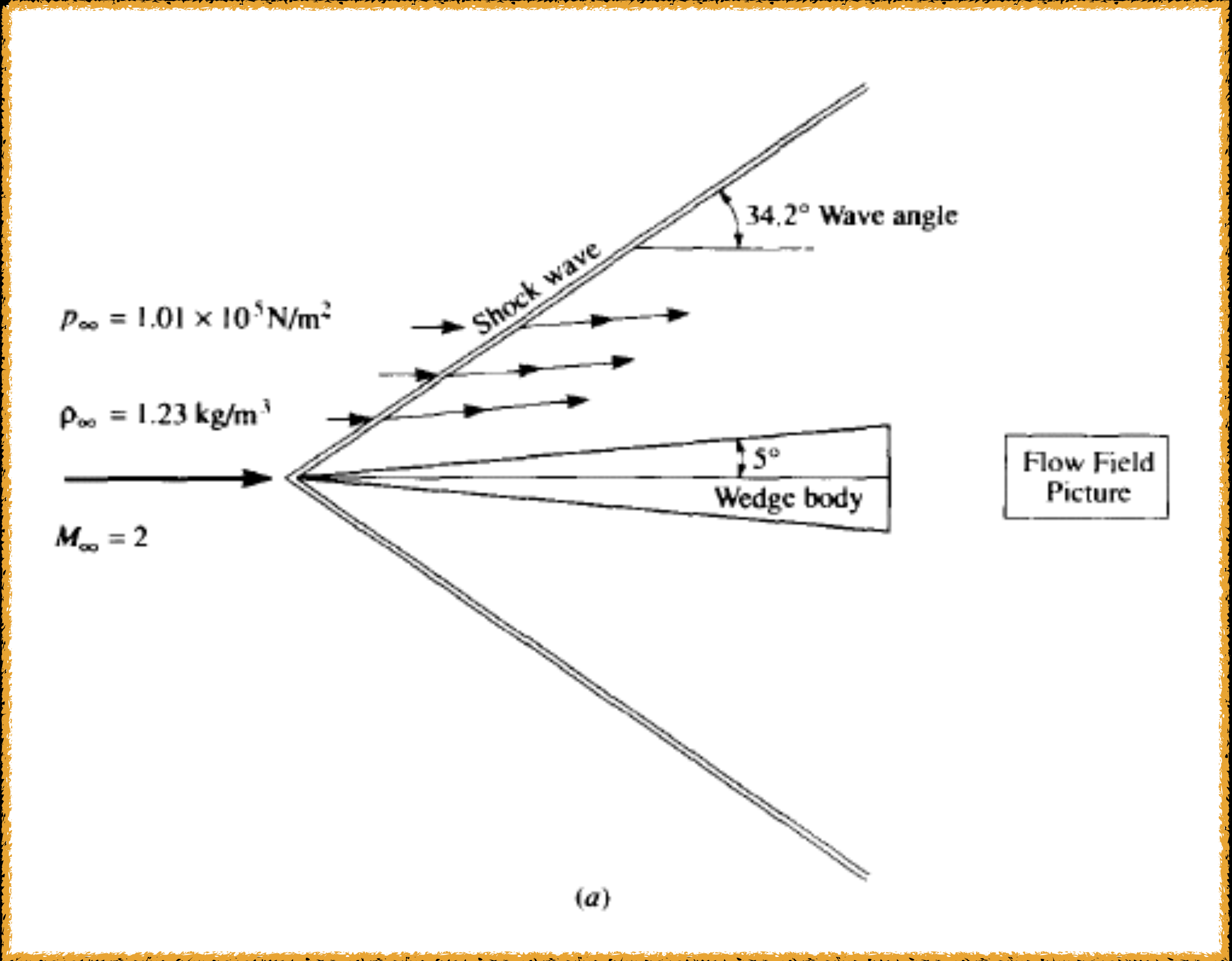
The lift and drag coefficients for 2D bodies are therefore given by:

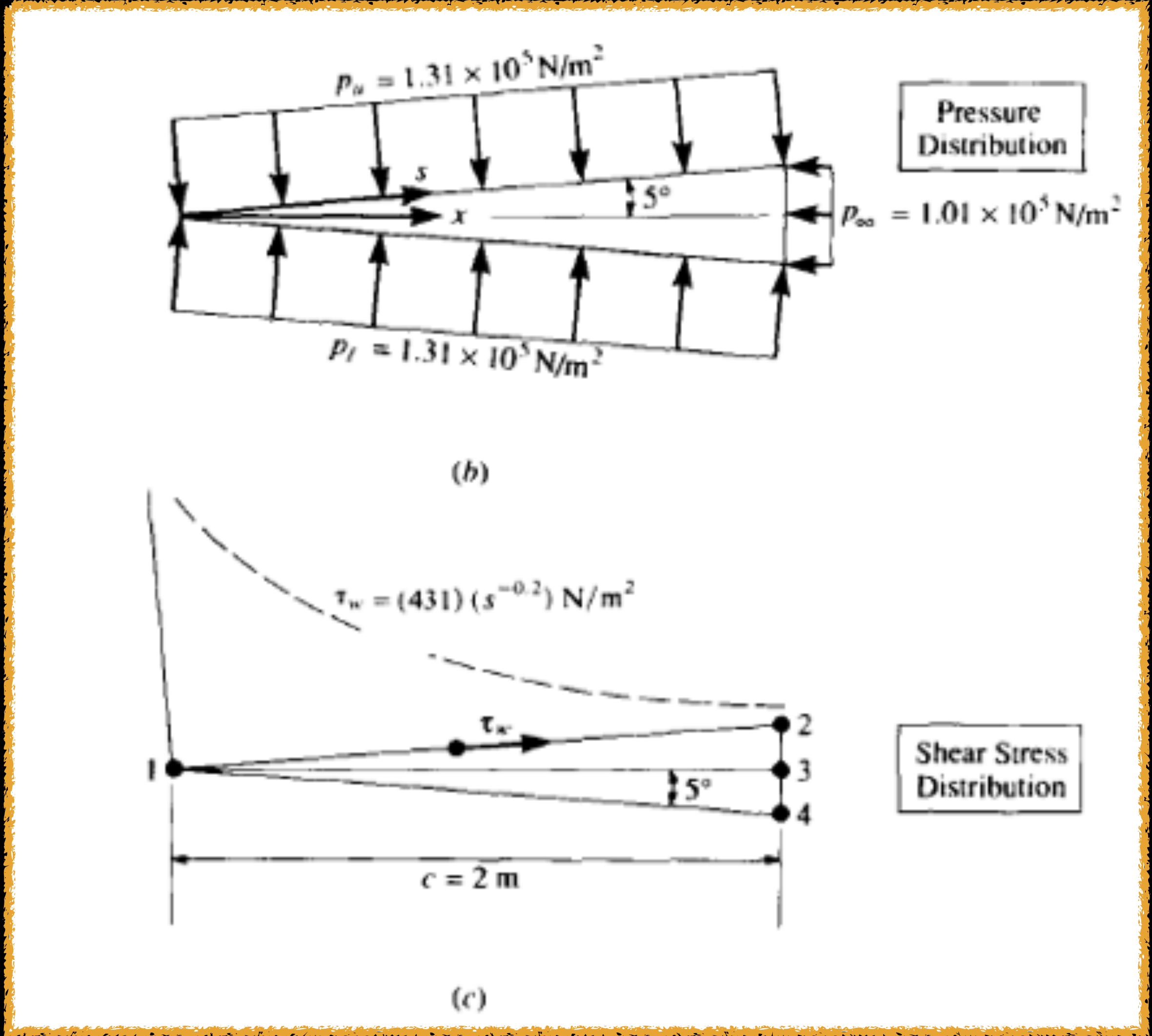
$$c_l = c_n cos\alpha - c_a sin\alpha$$

$$c_d = c_n sin\alpha + c_a cos\alpha$$

The aerodynamic force and moment coefficients can be obtained by *integrating pressure & skin friction coefficients over the body.*

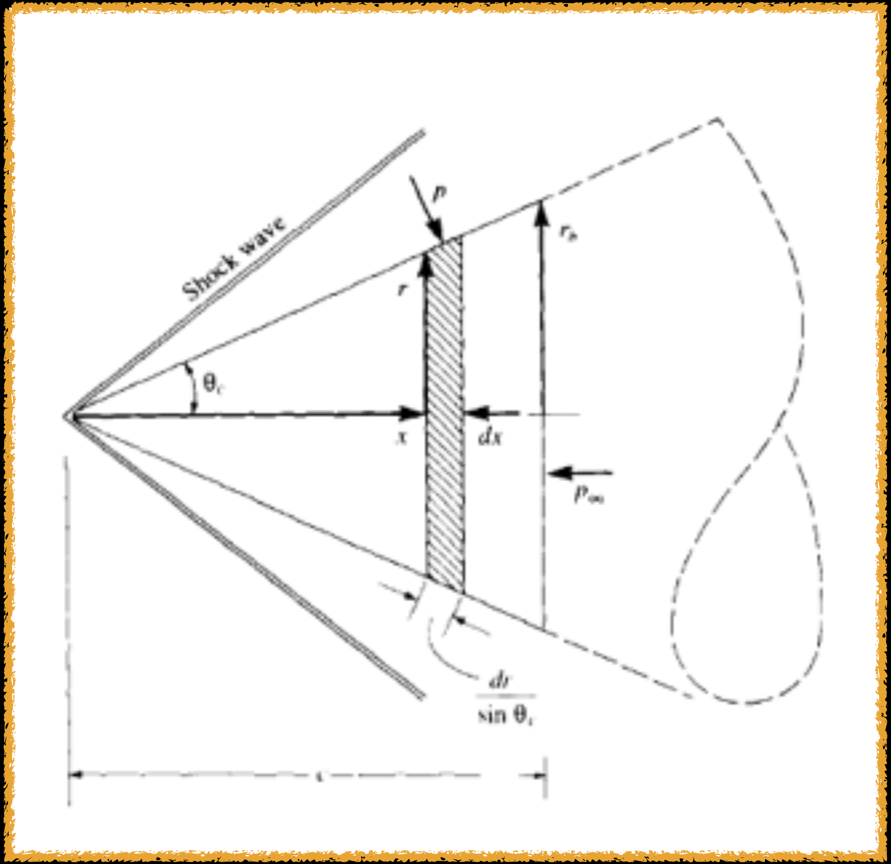
Example

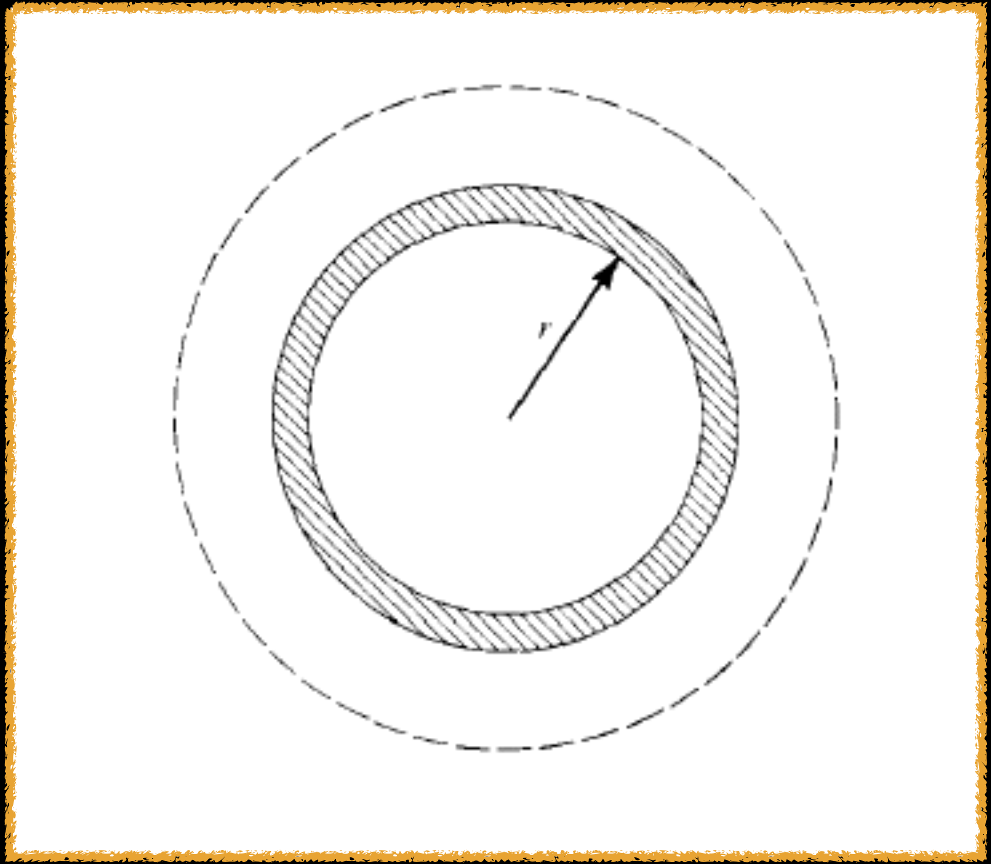




Calculate the drag coefficient for the wedge.

Example





Pr. coeff. on the surface of a hypersonic body (Newtonian sine squared):

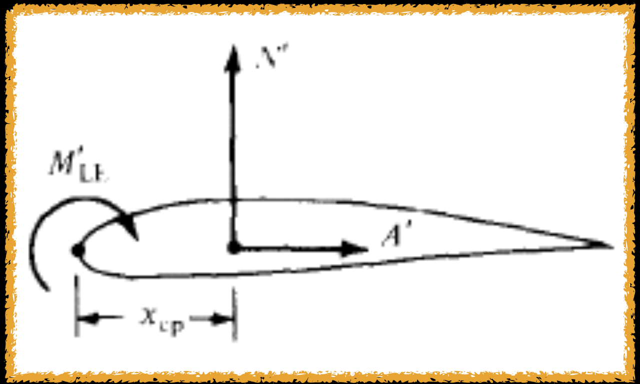
$$C_p = 2sin^2\theta_c$$

Assume C_p (hence pr.) is constant, $p = p_{inf}$ at the base.

Calculate the drag coefficient for the cone.

Center of Pressure

Can the distributed load over a body be replaced by a single force (or its components)?



The replaced force (or its components) must also be able to generate the same moment about the LE as shown by our equations.

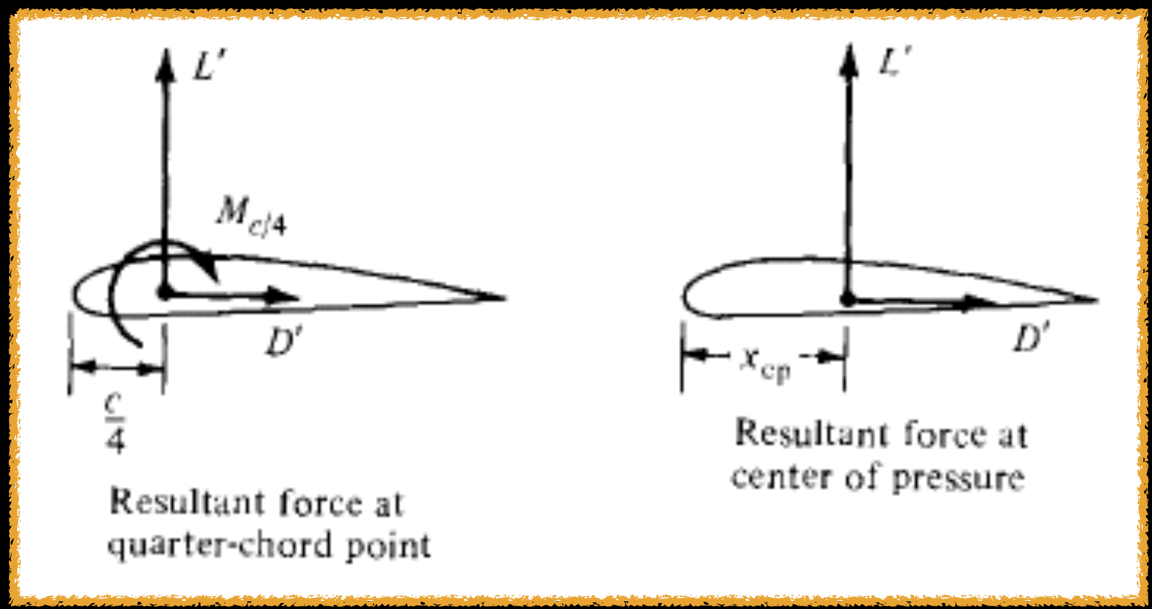
$$M'_{LE} - N' x_{cp} = 0$$

$$x_{cp} = \frac{M'_{LE}}{N'}$$

x_{cp} *is the center of pressure: Point on the body about which the aerodynamic moment is zero.*

Center of Pressure

The replaced force (or its components) can be placed at any point on the body as long as the moment at that point is also known.



$$M'_{LE} = -\frac{c}{4}L' + M'_{c/4} = -x_{cp}L'$$

For later: For a thin airfoil (symmetric), the center of pressure is at the quarter-chord location.

Center of Pressure: Example

Low-Speed, incompressible flow over NACA 4412 airfoil

$$\alpha = 4^o$$

$$c_l = 0.85$$

$$c_{m,c/4} = -0.09$$

Calculate the location of location of the center of pressure.

Buckingham PI Theorem

What physical quantities determine the variation of forces and moments? - Dimensional Analysis

1. *Select the dimensional parameters (n).*
2. *Select primary dimensions (r = 3).*
3. *Write down the dimensions of each dimensional parameter.*
4. *Select 'm' dimensional parameters that are primarily different from each other.*
5. *Set up 'n-m' non-dimensional parameters.*

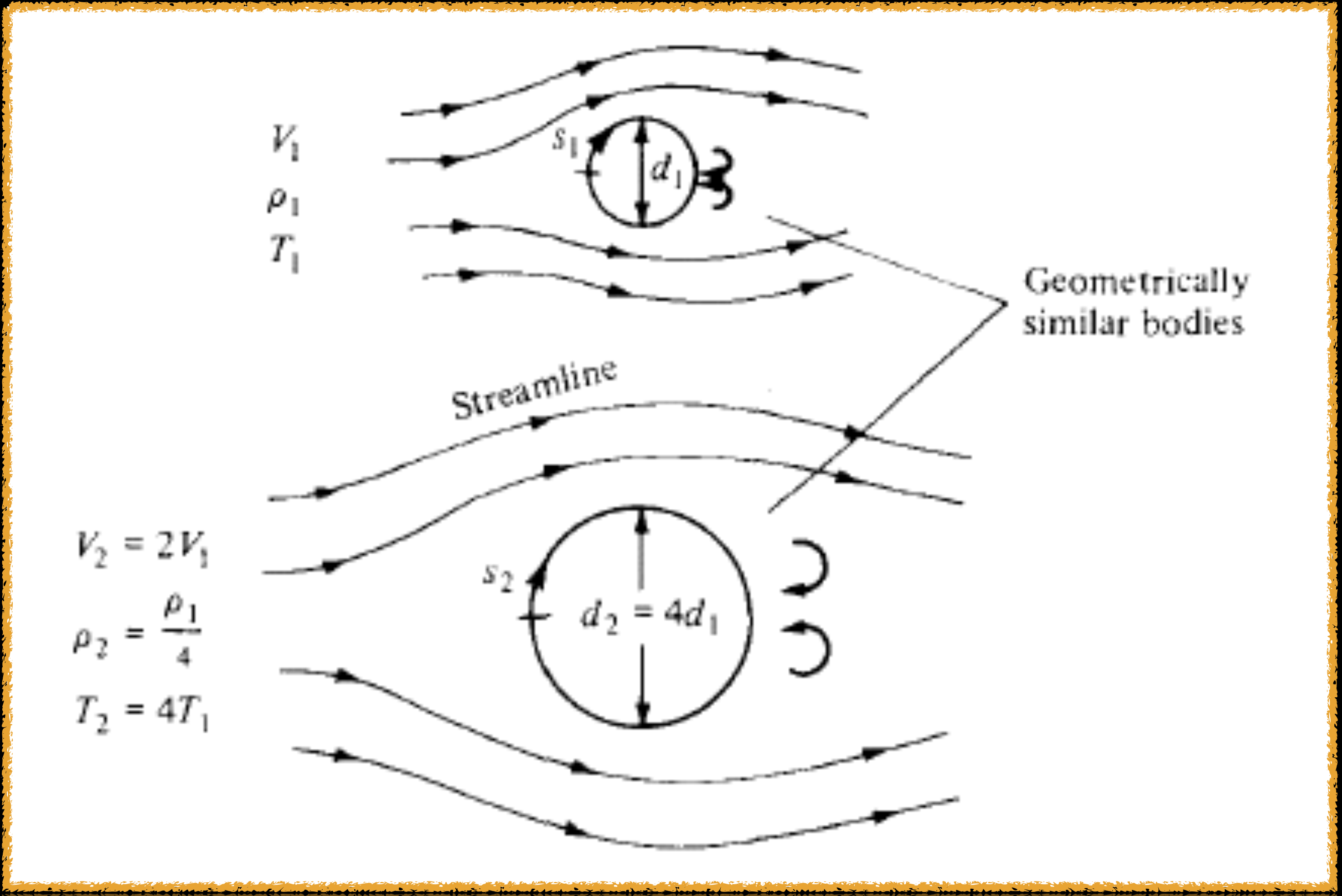
Dynamically Similar Flows

Consider different flows over a model and a prototype.

The flows are dynamically similar if:

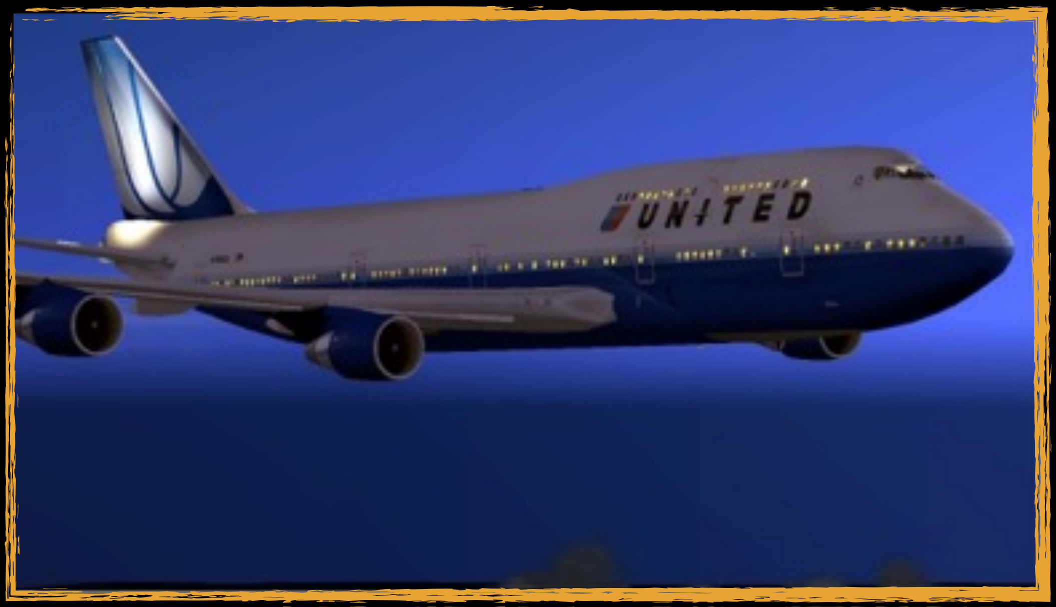
1. *The bodies have geometric similarity.*
2. *Streamline patterns are geometrically similar.*
3. *Distributions of non-dimensional velocity, pressure and temperature are the same when plotted against the same non-dimensional parameters.*
4. *The force coefficients (non-dimensional parameters) are same for both the flows.*

Dynamically Similar Flows: Example



Show that the two flows are dynamically similar.

Dynamically Similar Flows: Example

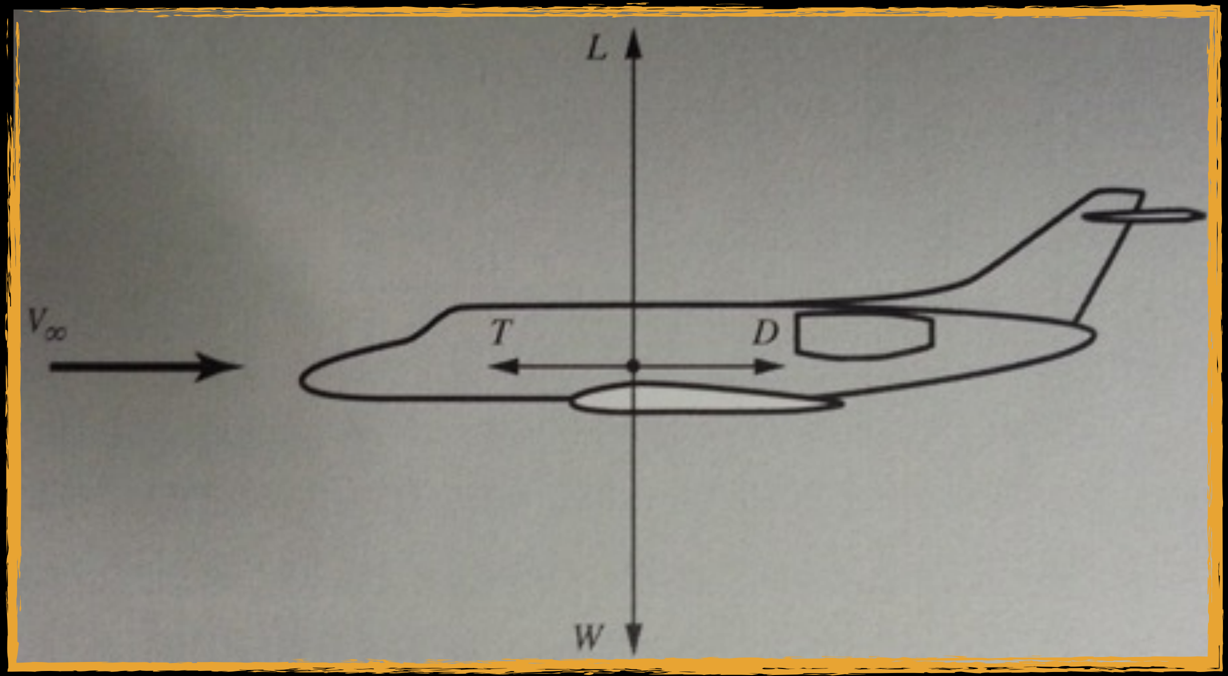


1. *Boeing 747 at cruising velocity of 550mi/h, 38000ft.*
2. *Freestream pressure and temperature: 432.6lb/ft^2 and 390R.*
3. *1/50th scale model is tested where temperature is 430R.*

Calculate velocity and pressure in the tunnel such that lift and drag coefficients are the same.

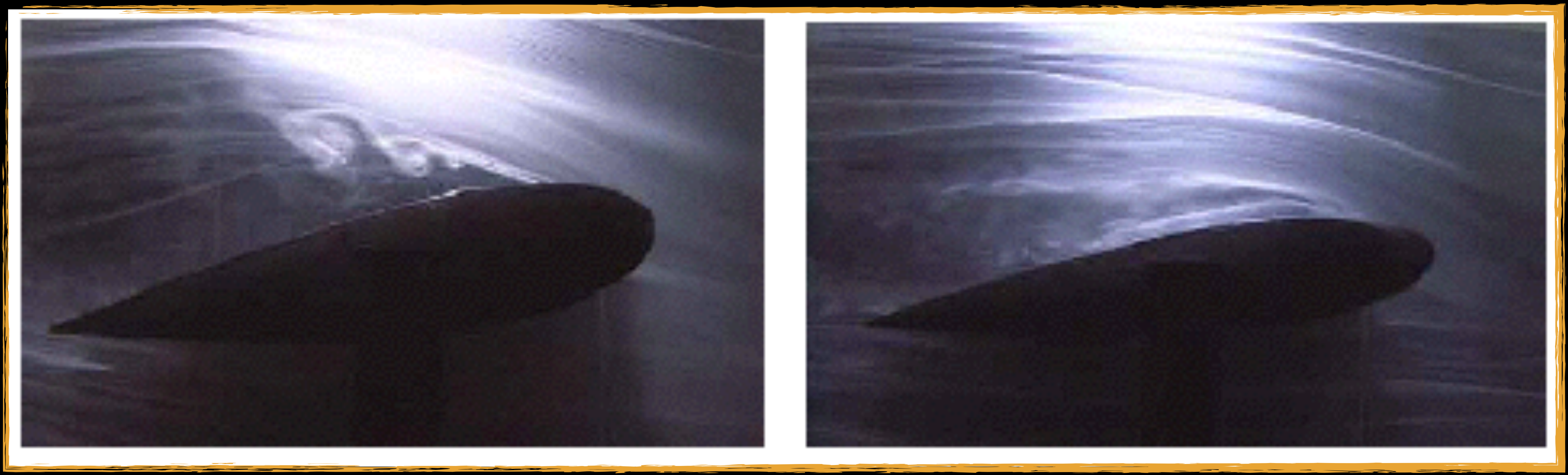
Lift and Drag Coefficients

- *C_D and C_L are fundamental quantities: intelligent design vs groping in the dark.*



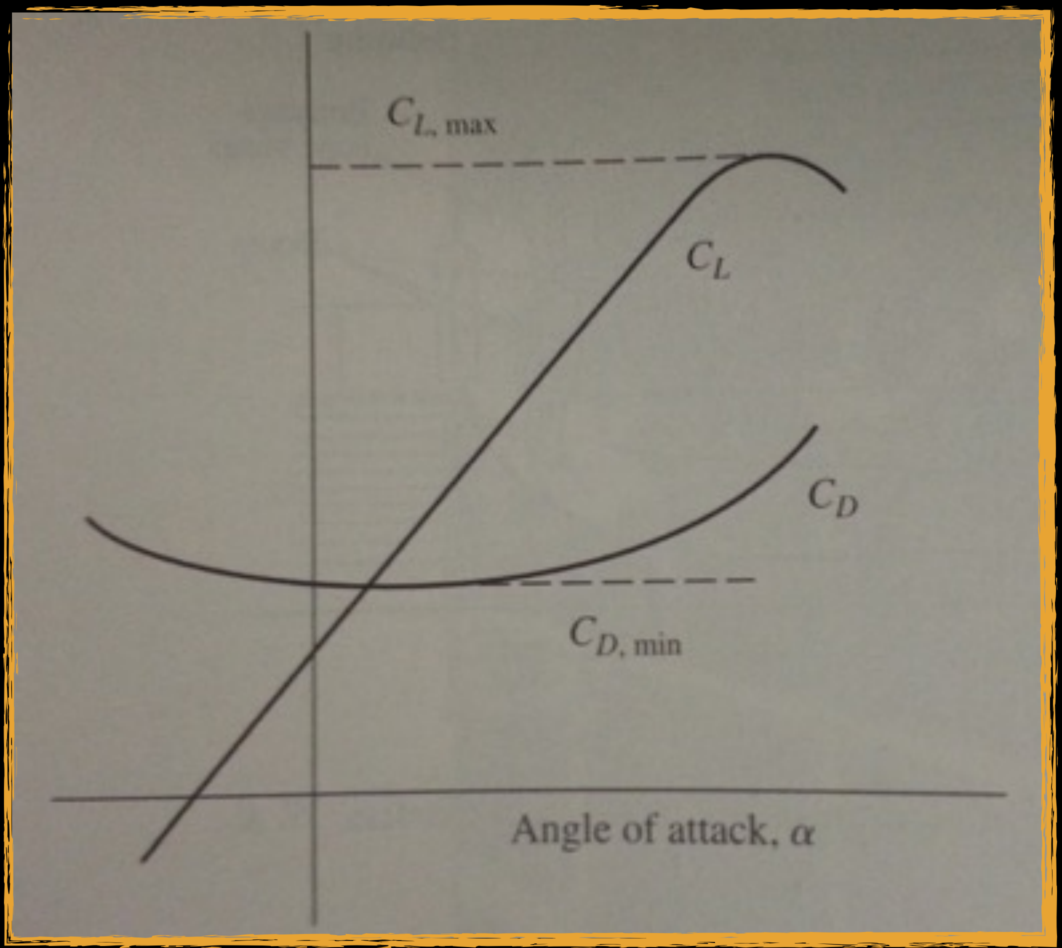
- *In order to sustain the airplane L = W.*
- *For steady (unaccelerated flight) T = D.*
- *Typically L/D = 15 - 20.*

Lift and Drag Coefficients



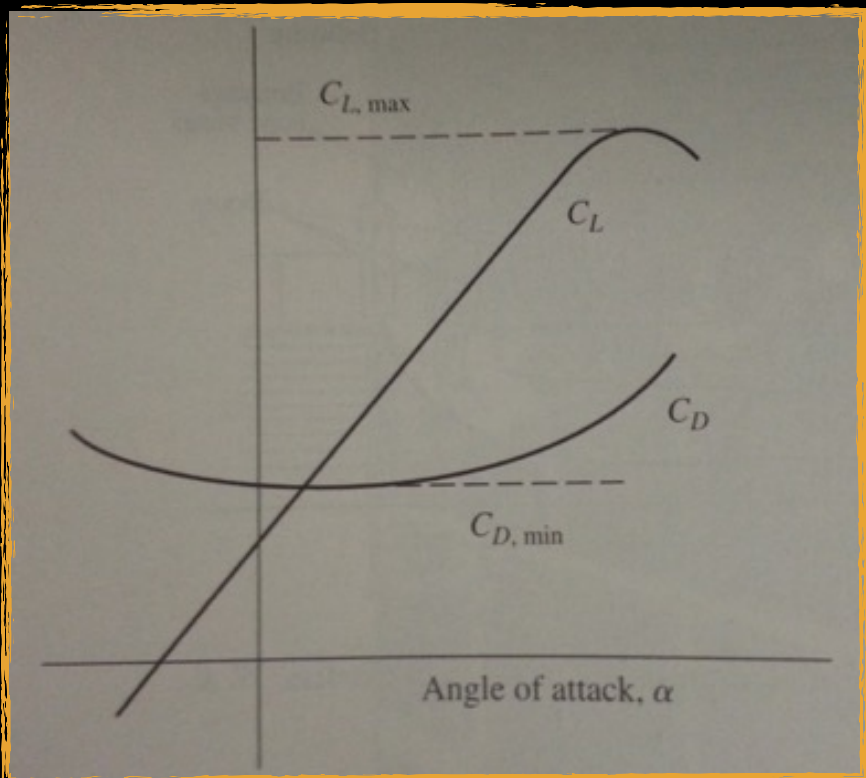
Lift and Drag Coefficients

- *For a given Reynolds and Mach number, C_D and C_L are only function of angle of attack (from dimensional analysis).*



- *C_L increases with angle of attack until the wing stalls (C_L reaches peak value: $C_{L,\max}$).*
- *Lowest possible velocity at which airplane can maintain steady, level flight is the stalling velocity, V_{stall}.*

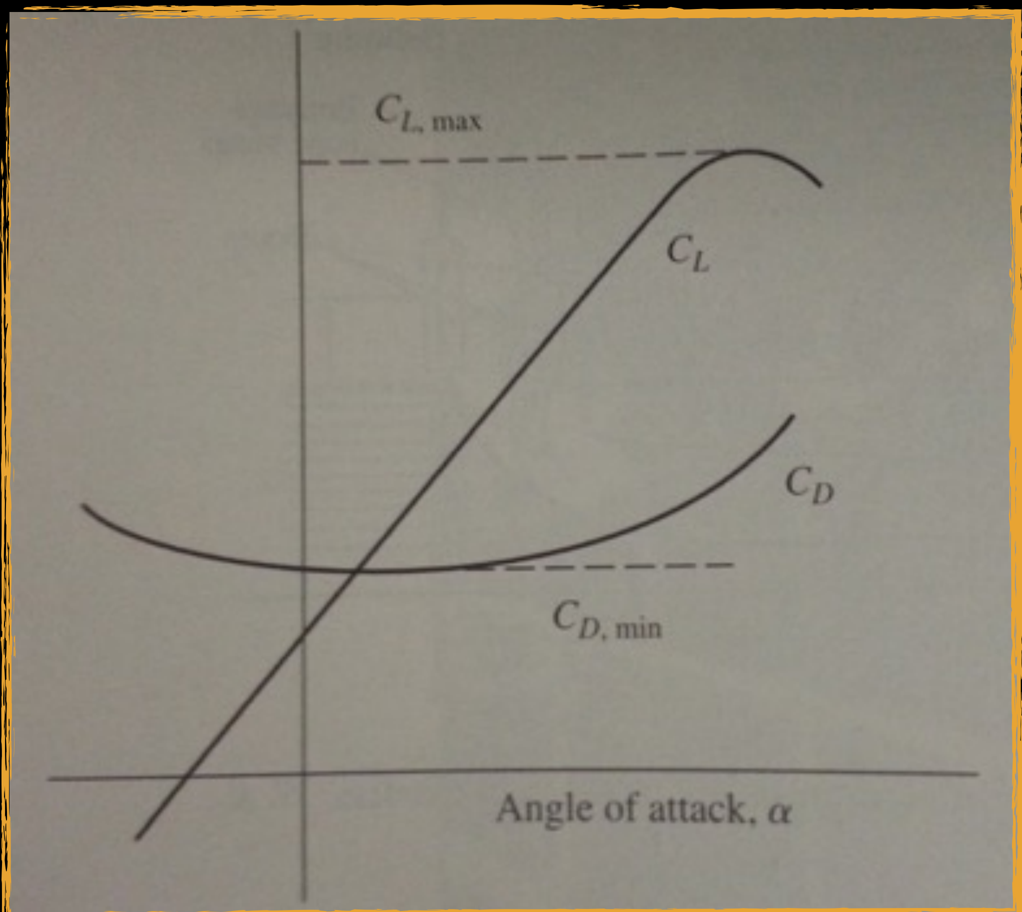
Lift and Drag Coefficients



$$V_{stall} = \sqrt{\frac{2W}{\rho_\infty S C_{L,max}}}$$

- *$C_{L,\,max}$ is purely determined by nature.*
- *High-lift devices such as flaps, slats and slots can be also used to increase $C_{L,\,max}$.*

Lift and Drag Coefficients



- *$C_{D,\ min}$ determines the maximum thrust.*
- *For steady, level flight $T = D$.*

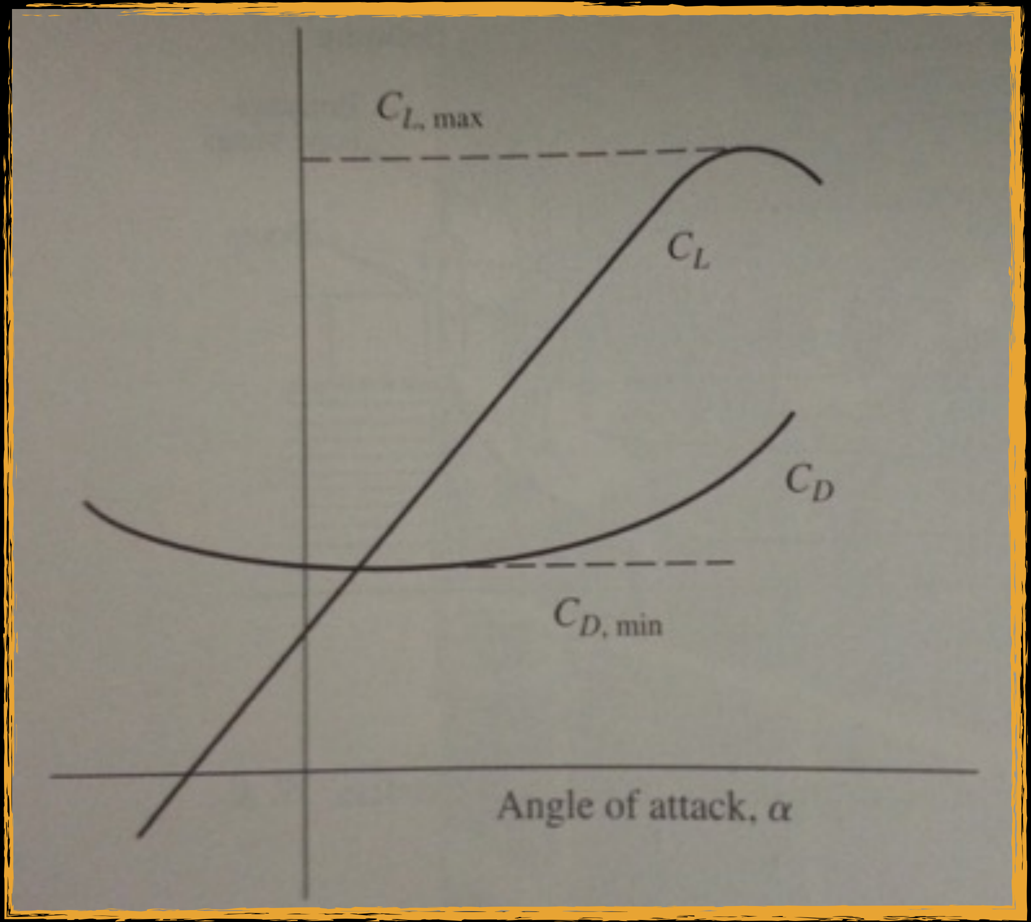
$$C_D = \frac{D}{q_\infty S} = \frac{T}{q_\infty S} = \frac{2T}{\rho_\infty V_\infty^2 S}$$

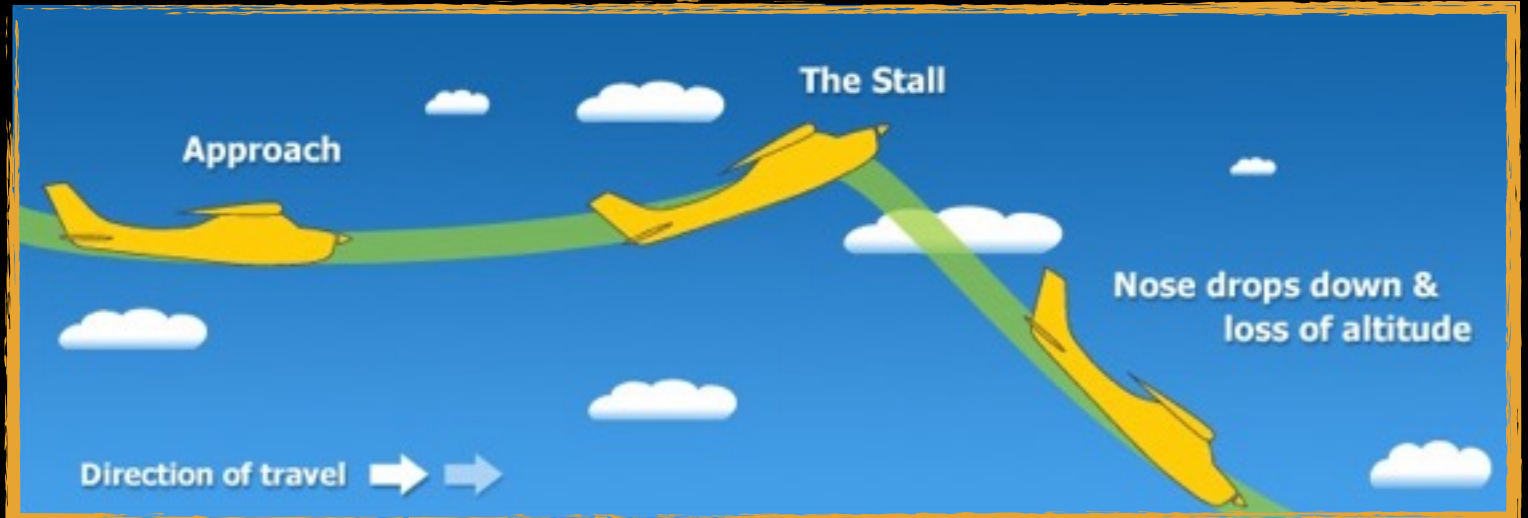
$$V_\infty = \sqrt{\frac{2T}{\rho_\infty S C_D}}$$

$$V_{max} = \sqrt{\frac{2T_{max}}{\rho_\infty S C_{D,min}}}$$

Lift and Drag Coefficients

- Stalling velocity is determined by $C_{L,\,max}$ and maximum velocity is determined by $C_{D,\,min}$.

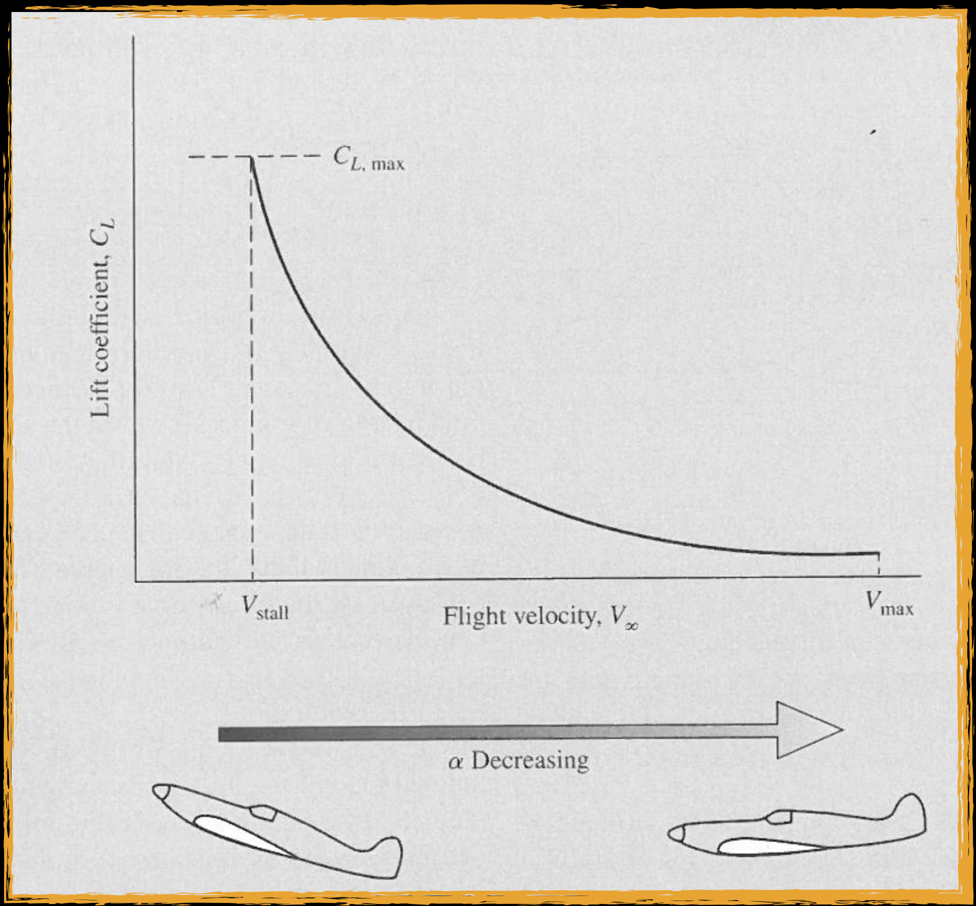




$$V_{stall} = \sqrt{\frac{2W}{\rho_\infty S C_{L,max}}}$$

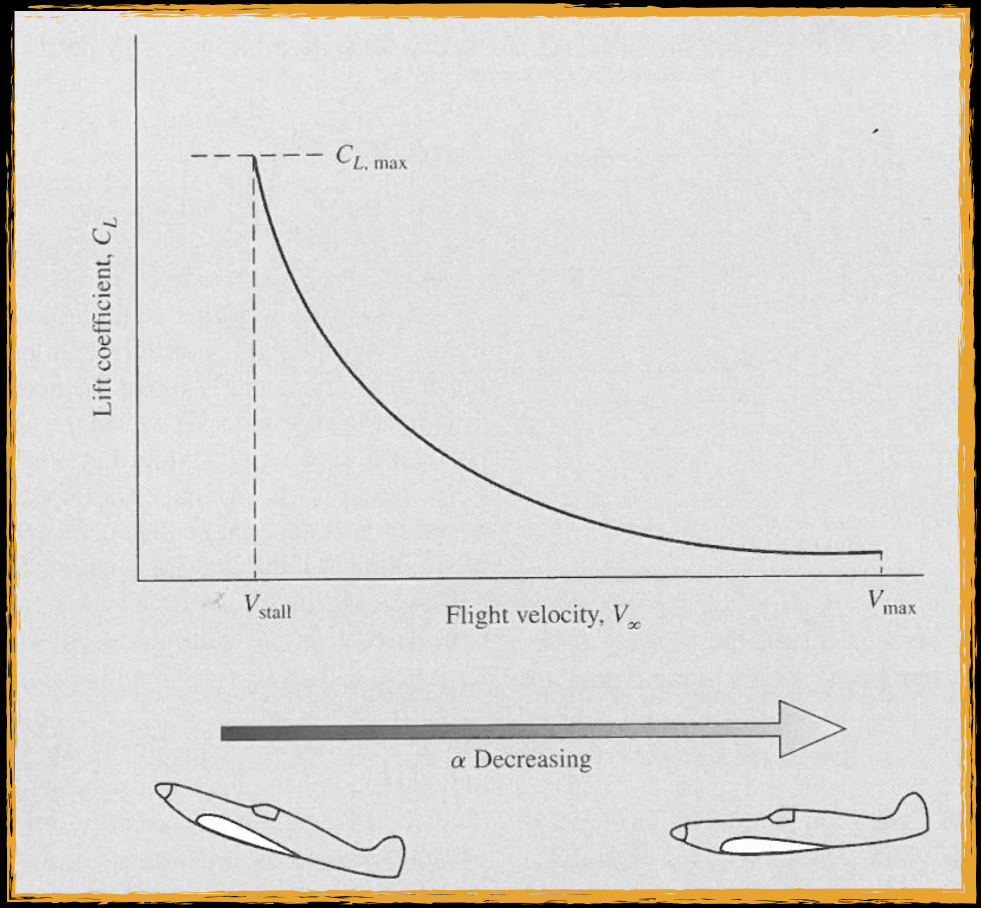
$$V_{max} = \sqrt{\frac{2T_{max}}{\rho_\infty S C_{D,min}}}$$

Lift and Drag Coefficients



- *Each flight velocity corresponds to a lift coefficient.*
- *At a given altitude, the values of C_L are what are needed to maintain a level flight.*
- *The airplane designer must achieve these values of C_L for a given weight and wing area.*

Lift and Drag Coefficients



slower

high α

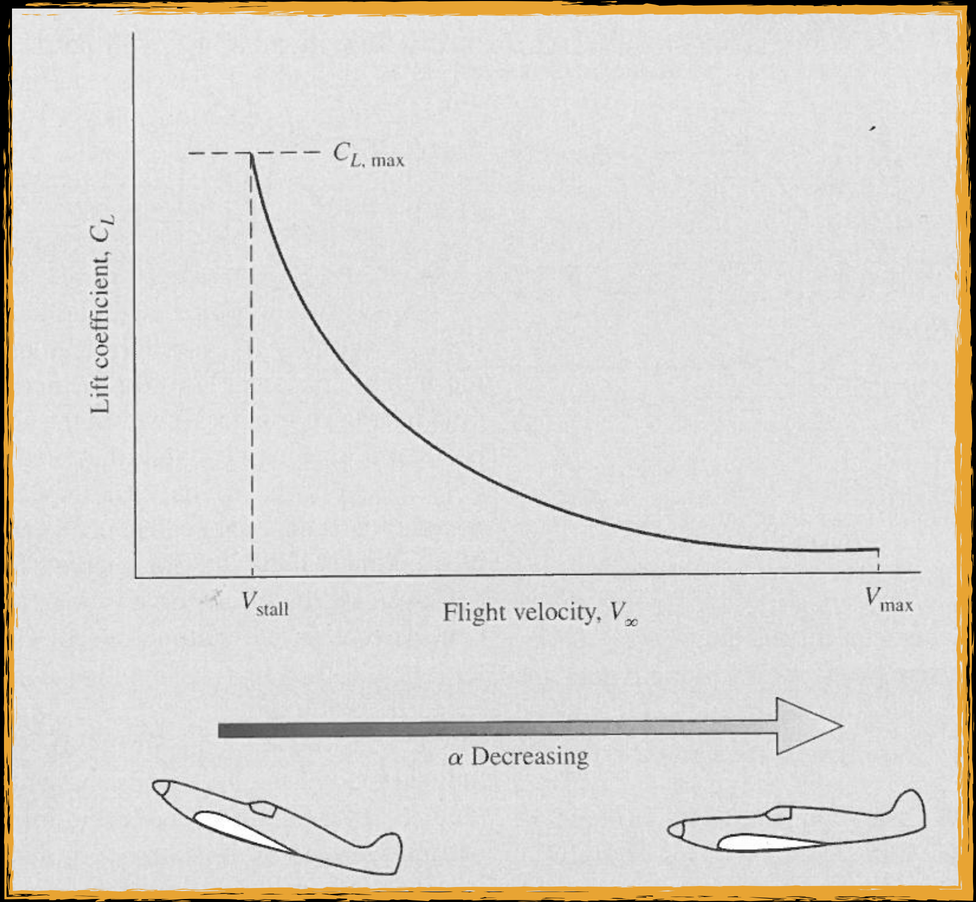
faster

low α

The specific angle of attack the airplane must have at a given flight velocity is dictated by specific value of C_L.

Lift and Drag Coefficients

- *Any "body" can generate lift at sufficient angle of attack for the range of velocities.*



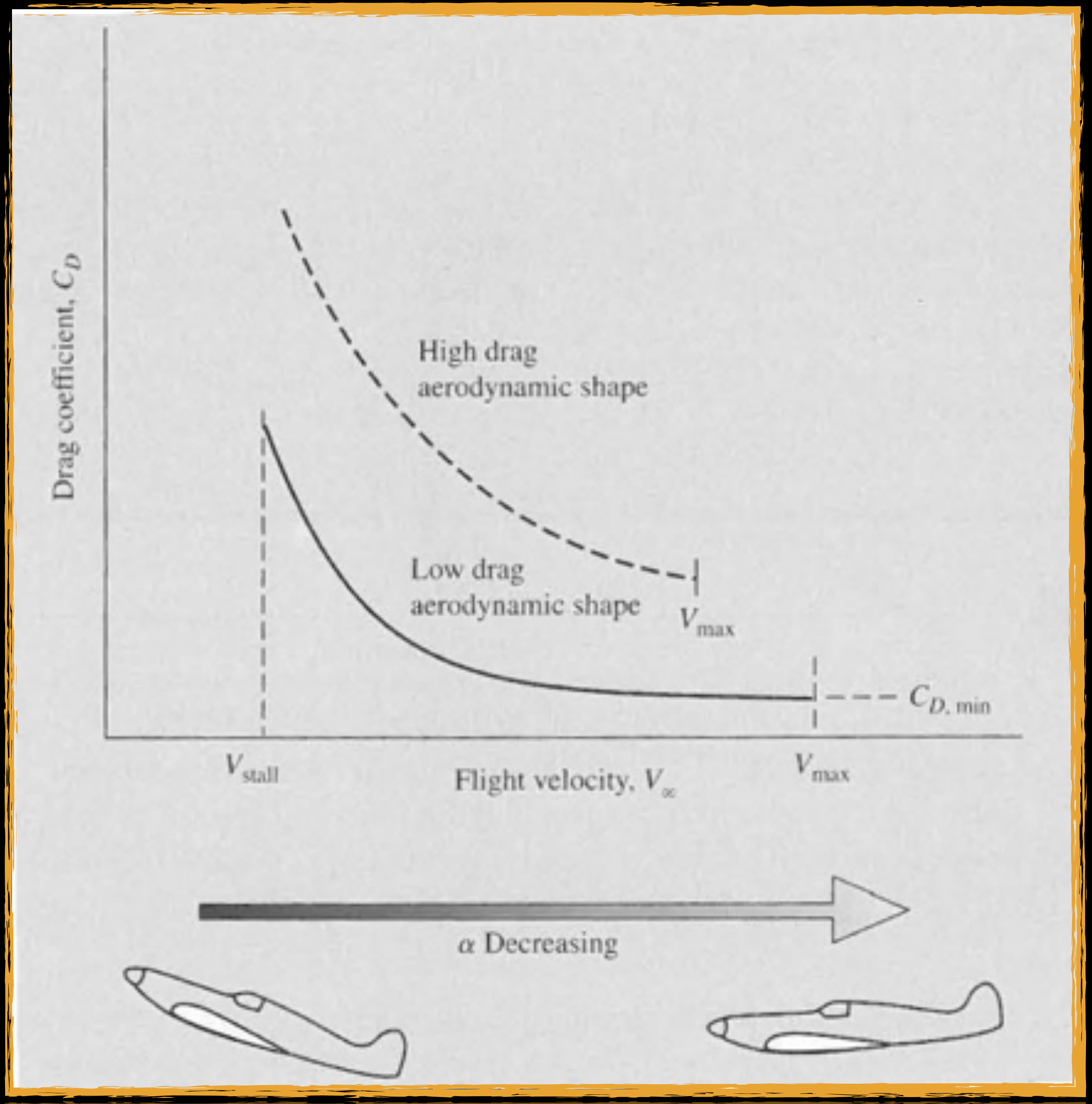
- *C_D is also varies with flight velocity.*

$$C_D = \frac{D}{q_\infty S} = \frac{T}{q_\infty S} = \frac{2T}{\rho_\infty V_\infty^2 S}$$

- *A poor aerodynamic shape can generate high amount of drag.*

Lift and Drag Coefficients

- *A poor aerodynamic shape can generate high amount of drag.*



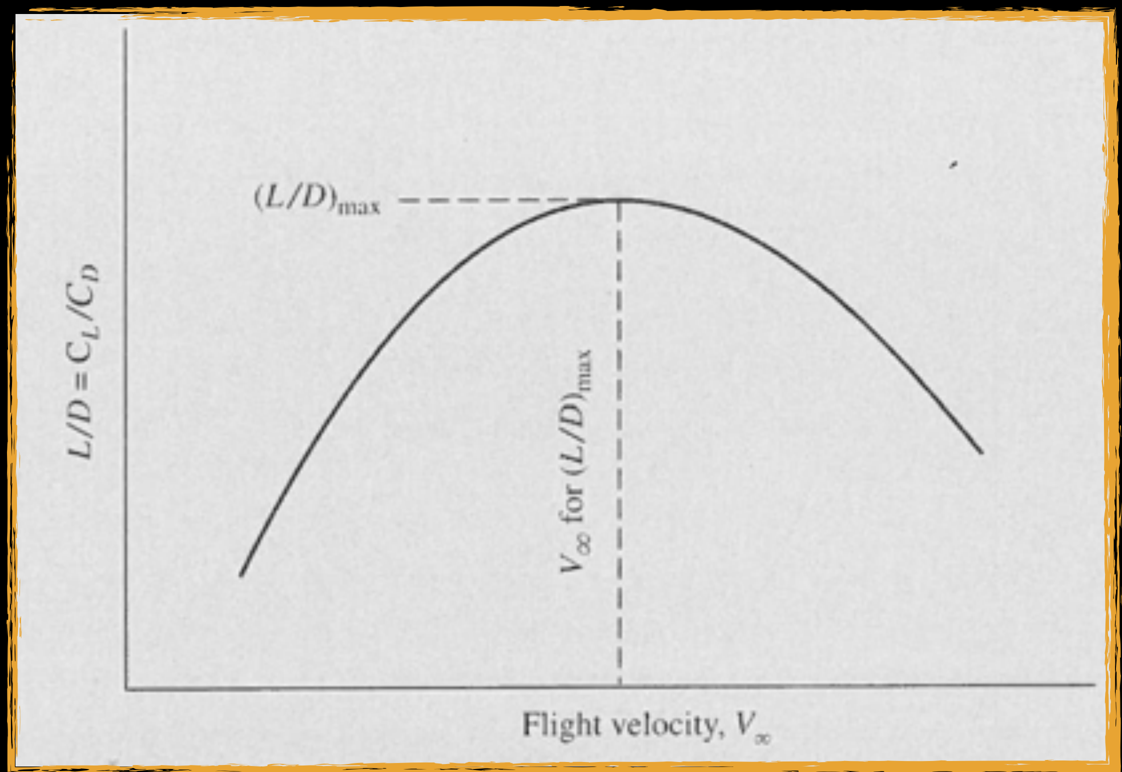
Lift to Drag Ratio

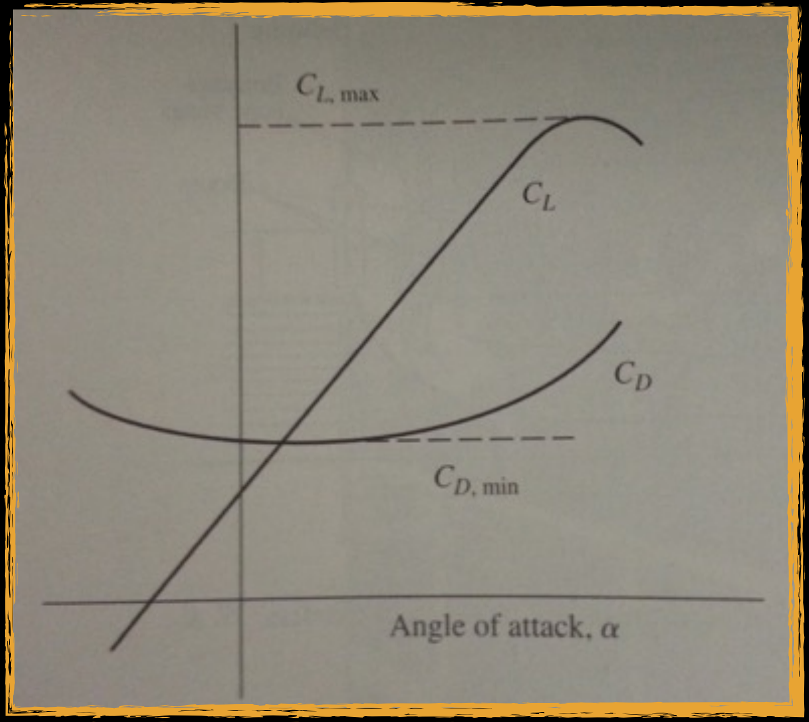
- *True measure of aerodynamic efficiency of a body shape is given by the lift-to-drag ratio.*

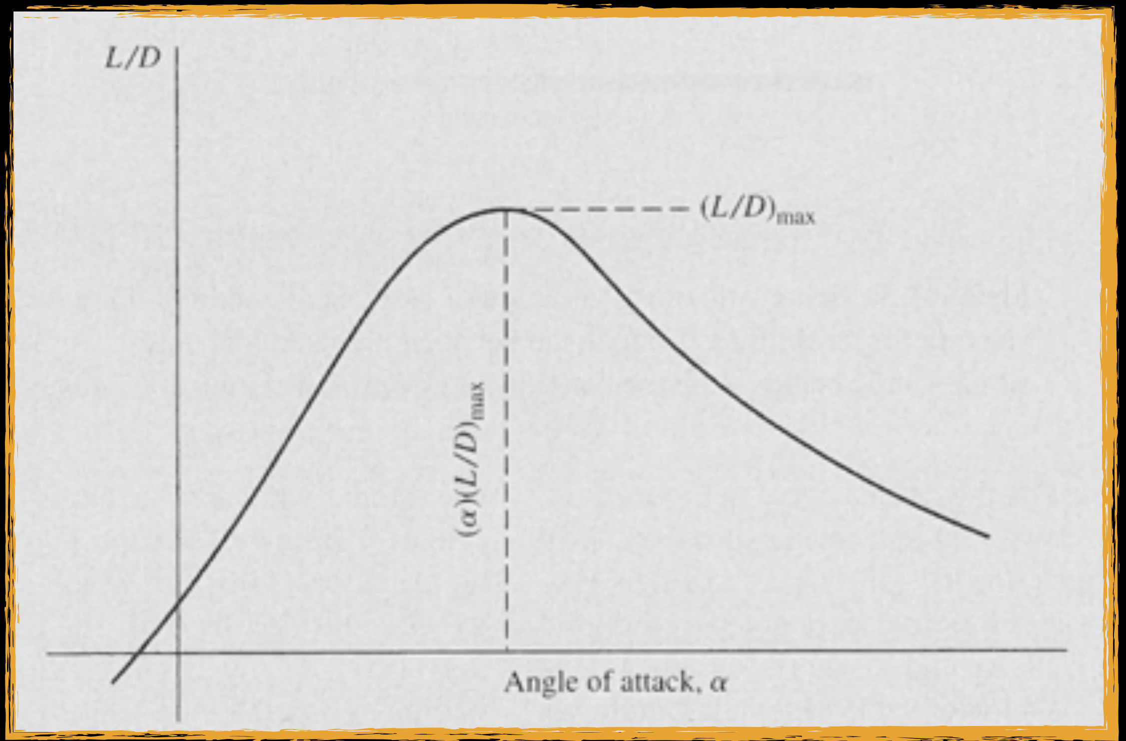
$$\frac{L}{D} = \frac{q_\infty S C_L}{q_\infty S C_D} = \frac{C_L}{C_D}$$

- *C_L: determined by airplane's W/S (wing loading).*
- *L/D is controlled by C_D at this velocity.*
- *We want a high L/D: an aerodynamically efficient body.*

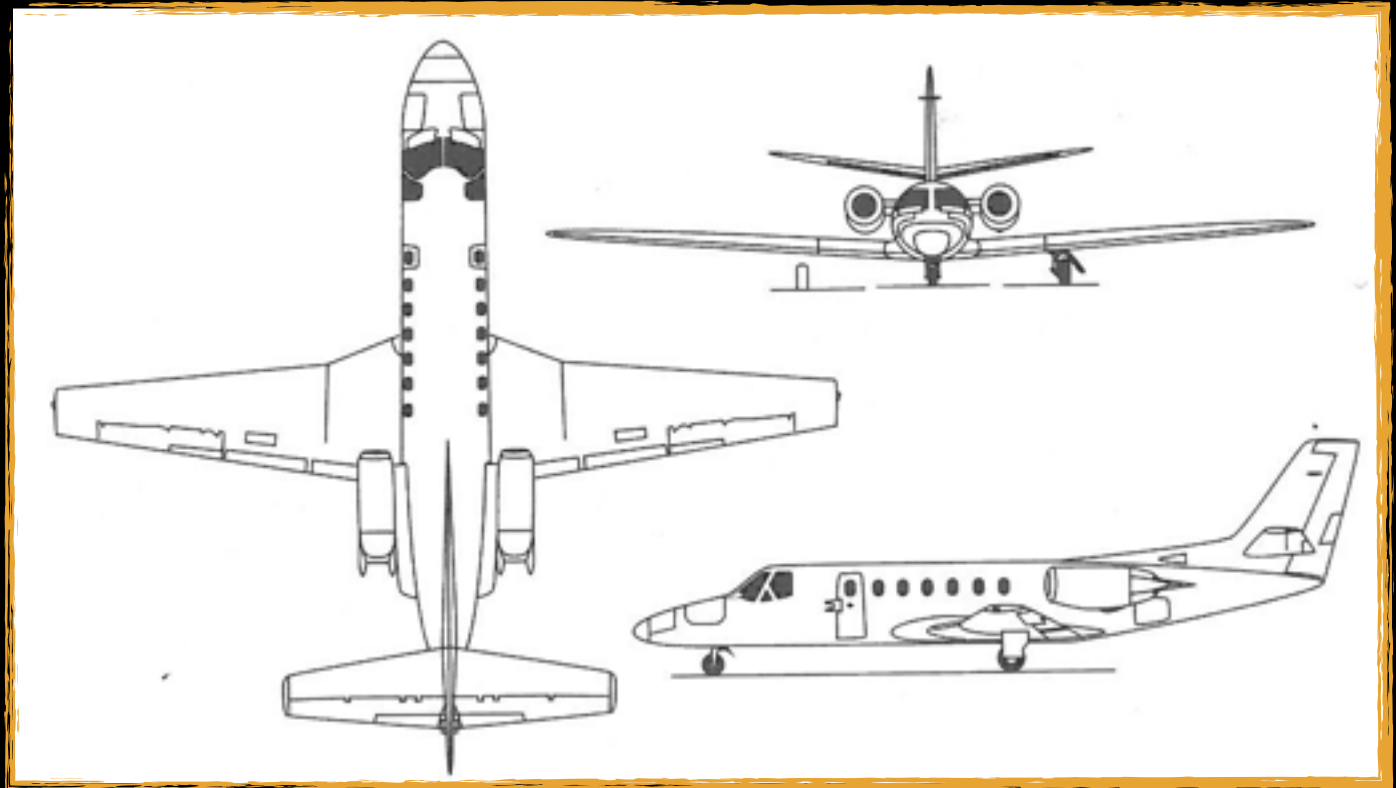
Lift to Drag Ratio







Lift to Drag Ratio: Example

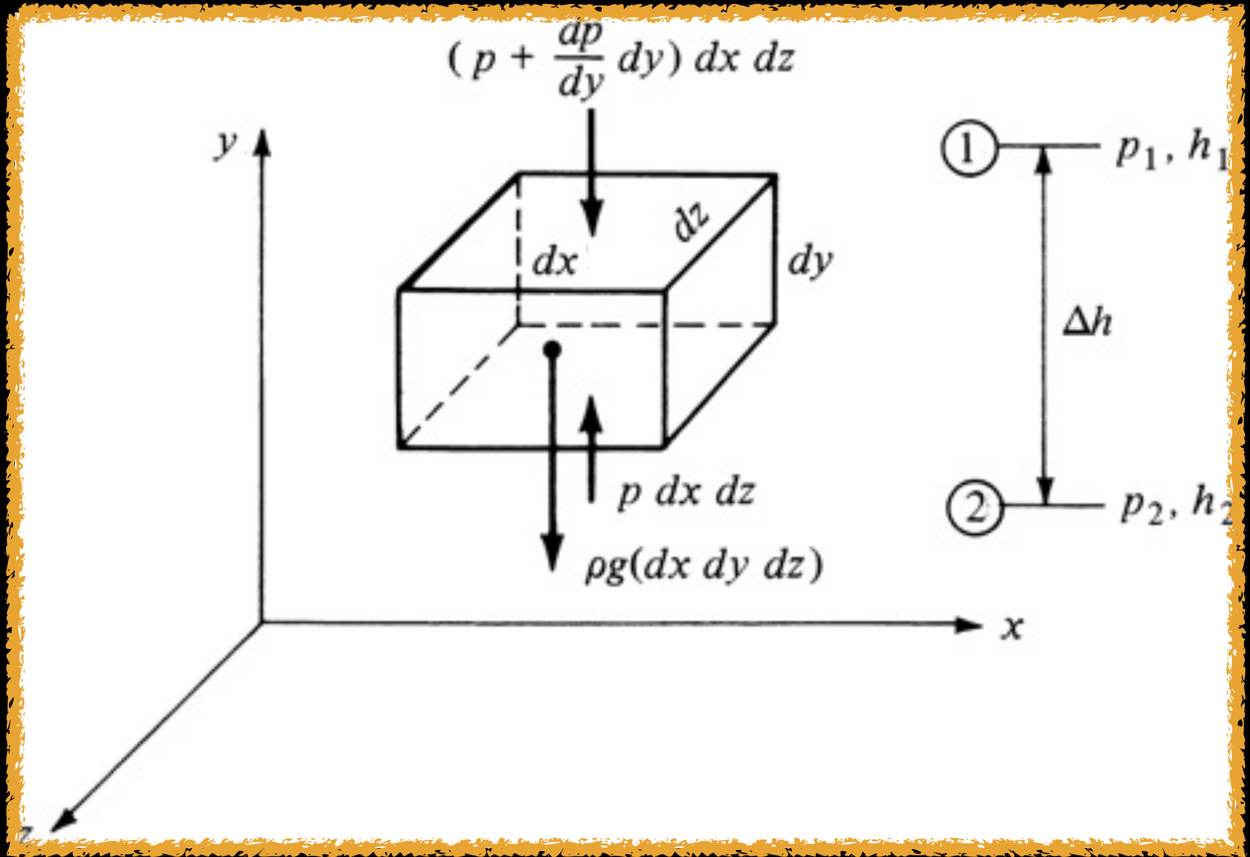


- *Cessna 560 cruising at 492mph at 33,000ft.*
- *Wing planform area is 342.6 sq.ft., weight is 15,000lb.*
- *Drag coefficient at cruise is 0.015.*

Calculate lift coefficient and L/D ratio.

Buoyancy Force

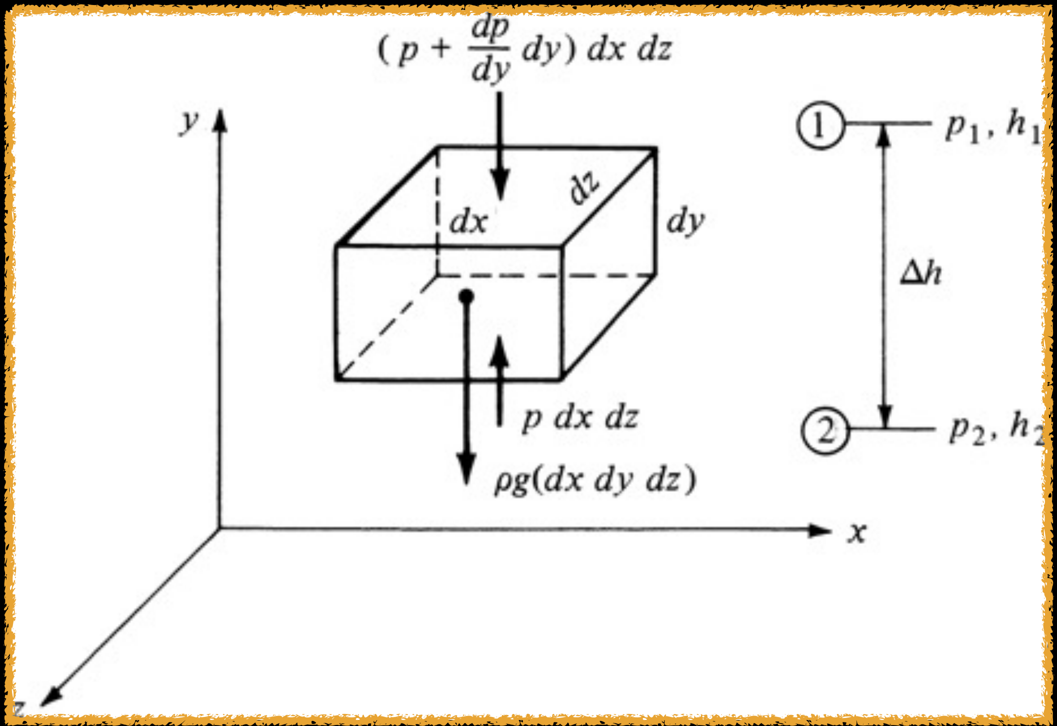
- *What are the forces acting on a body when there is no relative motion between the body and the fluid medium?*



$$Sum\ of\ forces: \quad -\frac{dp}{dy}(dx\ dy\ dz) - g\rho(dx\ dy\ dz) = 0$$

$$dp = -g\rho dy\ (Hydrostatic\ equation)$$

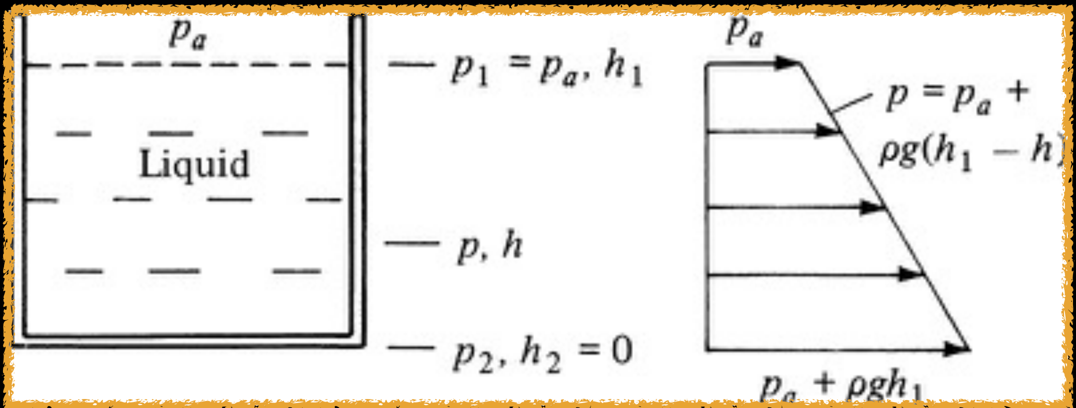
Buoyancy Force



$$dp = -g\rho dy \ (Hydrostatic\ equation)$$

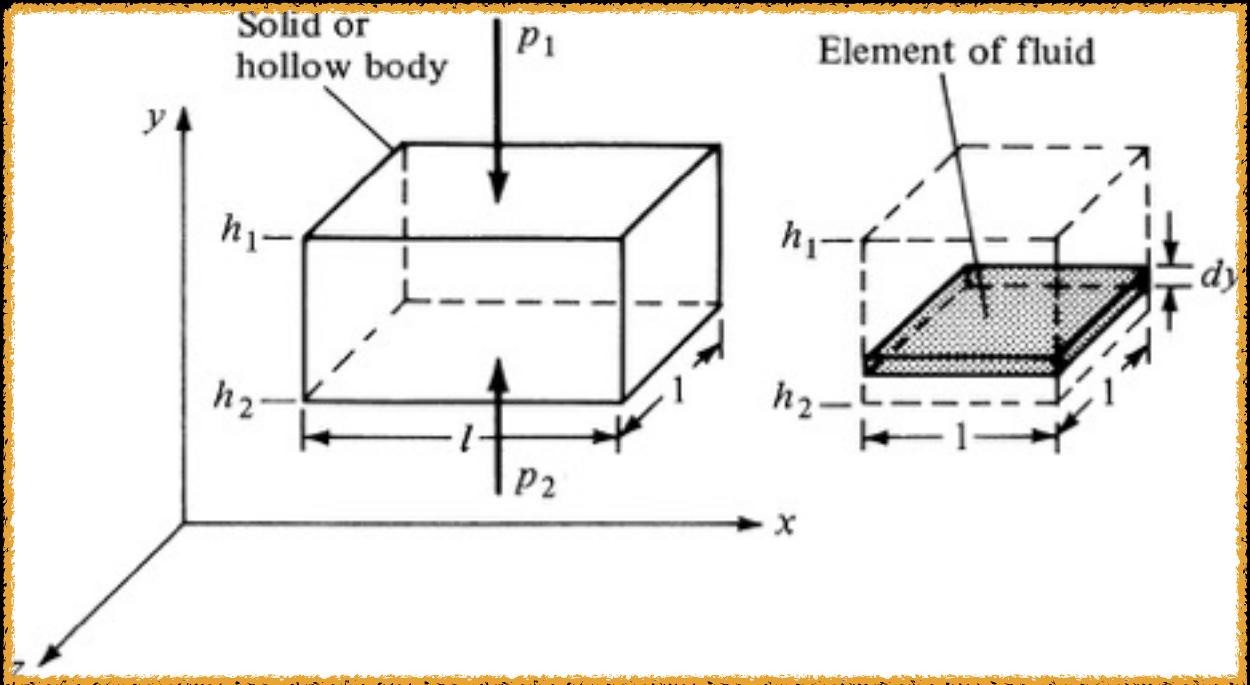
$$\int_{p_1}^{p_2} dp = -\rho g \int_{p_1}^{p_2} dy$$

$$p + \rho g h = const$$



$$p = p_a + \rho g(h_1 - h)$$

Buoyancy Force



- *A solid body immersed in a fluid experiences a force, buoyancy force, even if there is no relative motion.*

$$F = (p_2 - p_1)l(1)$$

$$= l\int_{p_1}^{p_2} dp$$

$$= l\int_{h_2}^{h_1} \rho g dy$$

Buoyancy Force = Weight of fluid displaced

Buoyancy Force: Example

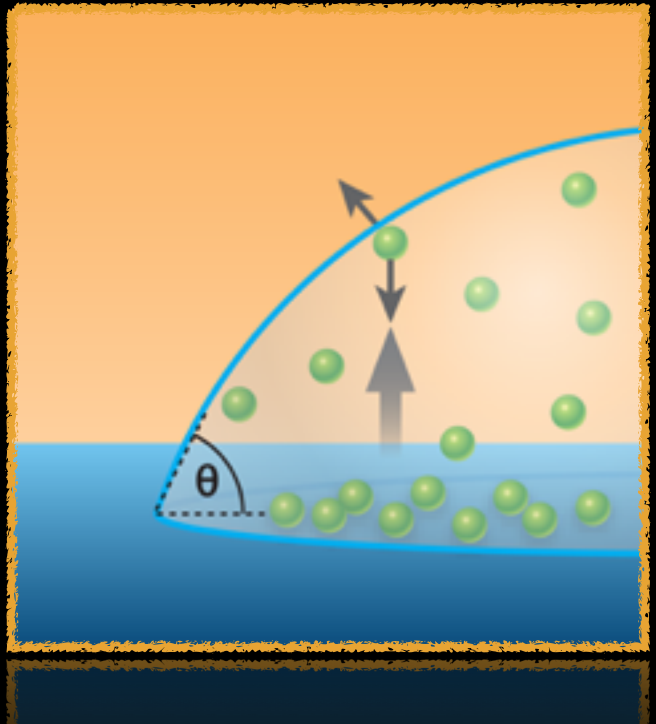
- *Hot-air balloon with an inflated diameter of 30ft carrying weight of 800lb.*
- *Calculate its upward acceleration and the achievable maximum altitude.*

$$\rho = 0.002377(1 - 7 \times 10^{-6} h)^{4.21}$$

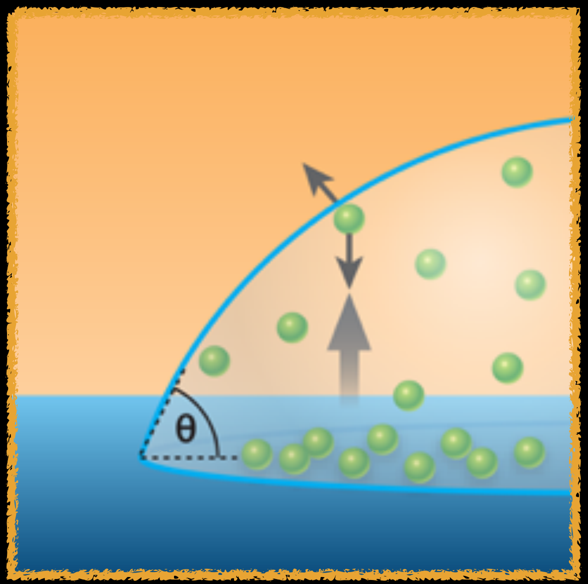
Types of Flow

Continuum vs. Free Molecule Flow

- *If the mean-free path is orders of magnitude smaller than the length scale of the body: continuum flow.*
- *If the mean-free path is of the same order of magnitude as the length scale of the body: free molecular flow.*



Inviscid vs. Viscous Flow



- *When molecules move, they transport their mass, momentum and energy from one location to another in a fluid.*
- *This transport on a molecular level gives rise to mass diffusion, viscosity (friction), and thermal conduction: Viscous Flows.*
- *Flow with no friction, thermal conduction or diffusion: Inviscid Flow.*

Inviscid vs. Viscous Flow

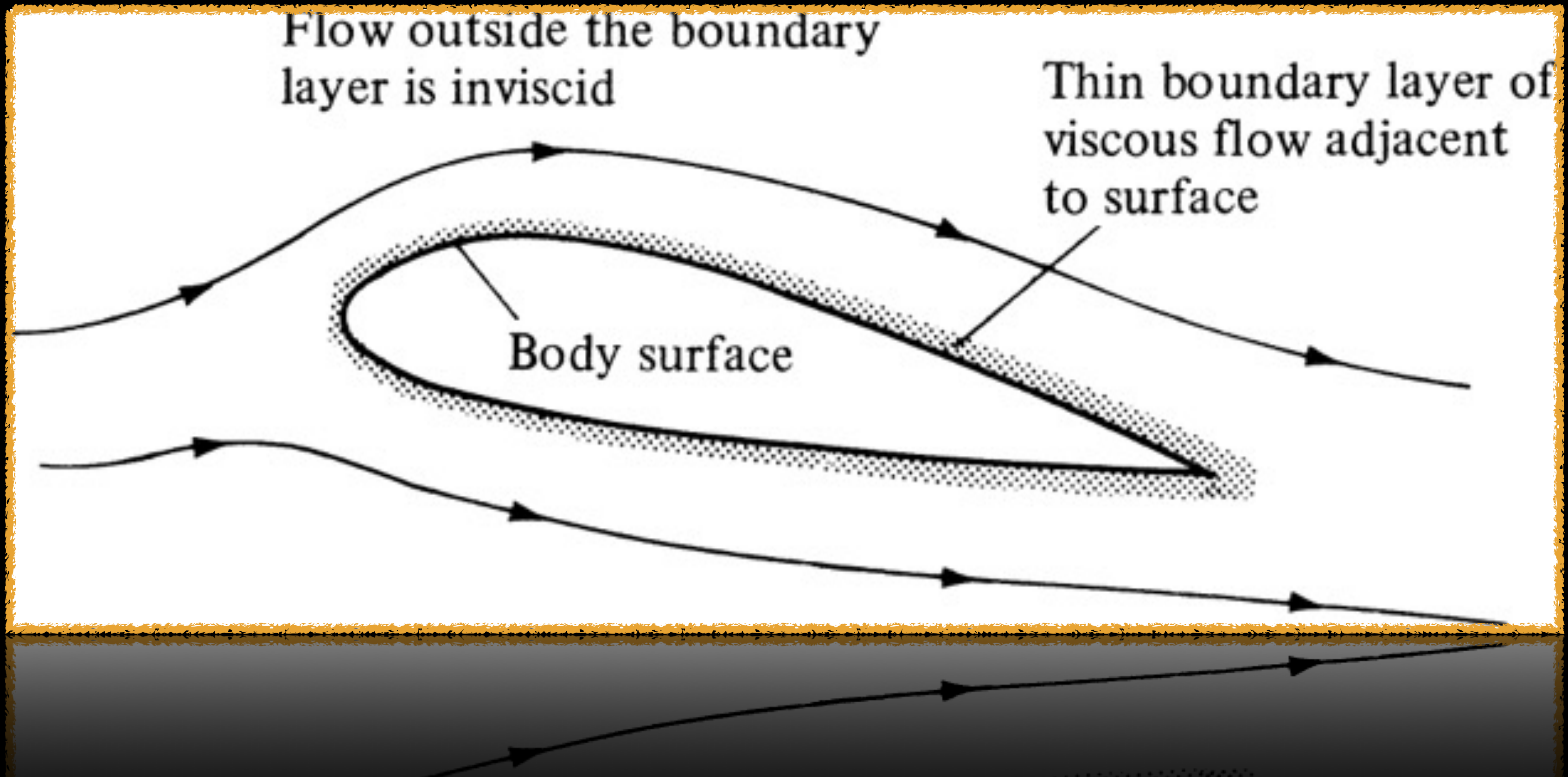
- *Inviscid flows do not truly exist in nature.*
- *However, there are many flows where the influence of transport phenomenal is small: flow can be modeled as inviscid flow.*

$$Re = \frac{\rho v d}{\mu}$$

- *Inviscid flow is realized when Re approached infinity.*
- *Many flows with high but finite Re can be assumed inviscid.*

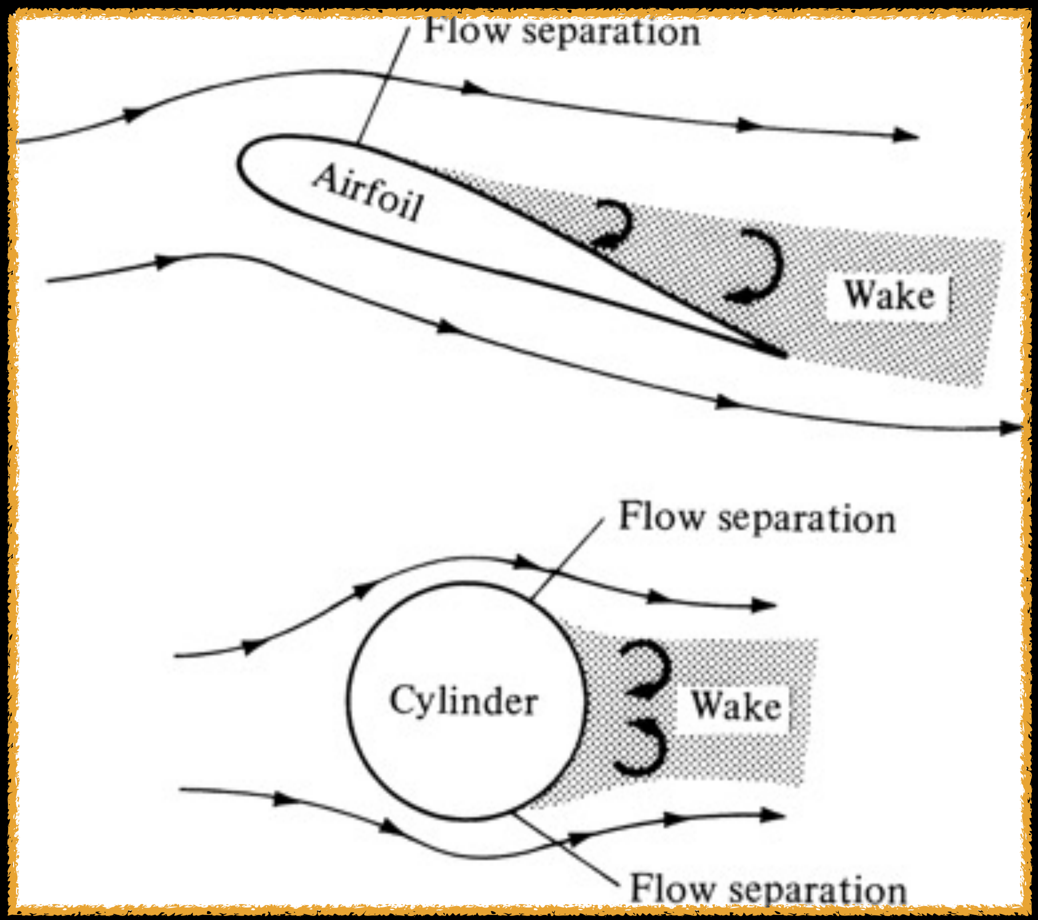
Inviscid vs. Viscous Flow

- *For such high Re flows, the influence of transport phenomena is limited to a very thin layer adjacent to the surface: boundary layer.*
- *Outside this layer, the flow can be assumed to be essentially inviscid.*



Inviscid vs. Viscous Flow

- *In contrast, some flows can be dominated by viscous effects.*

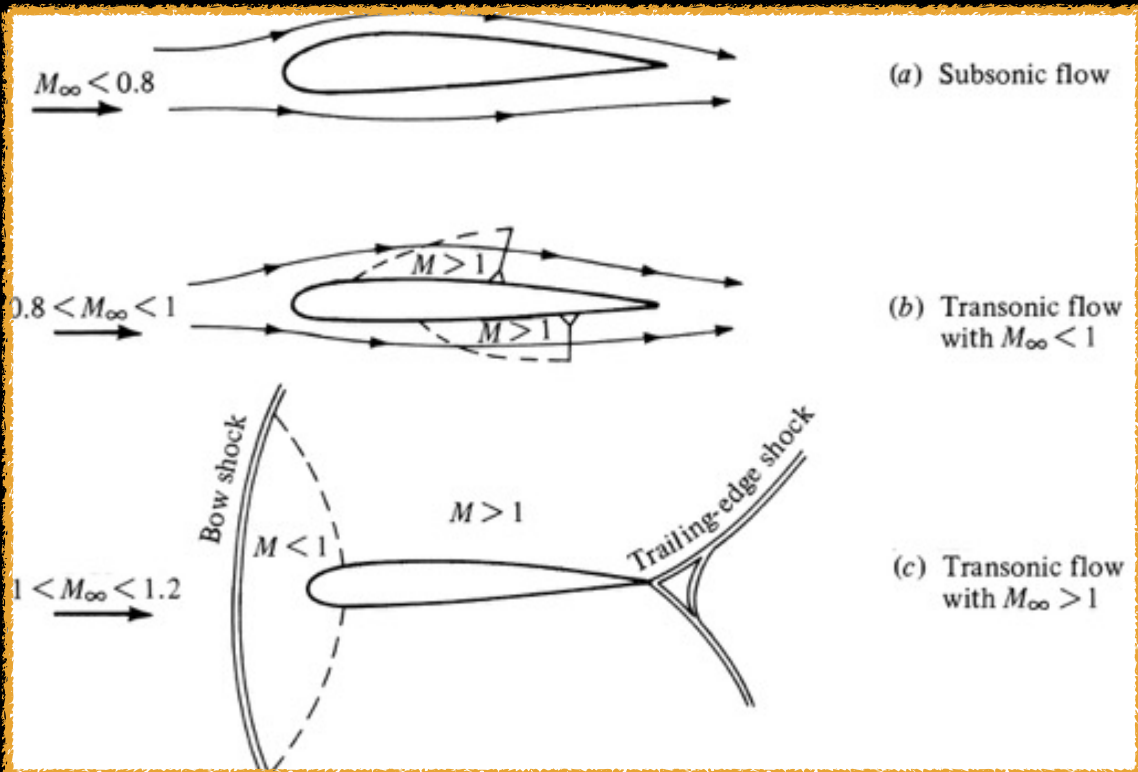


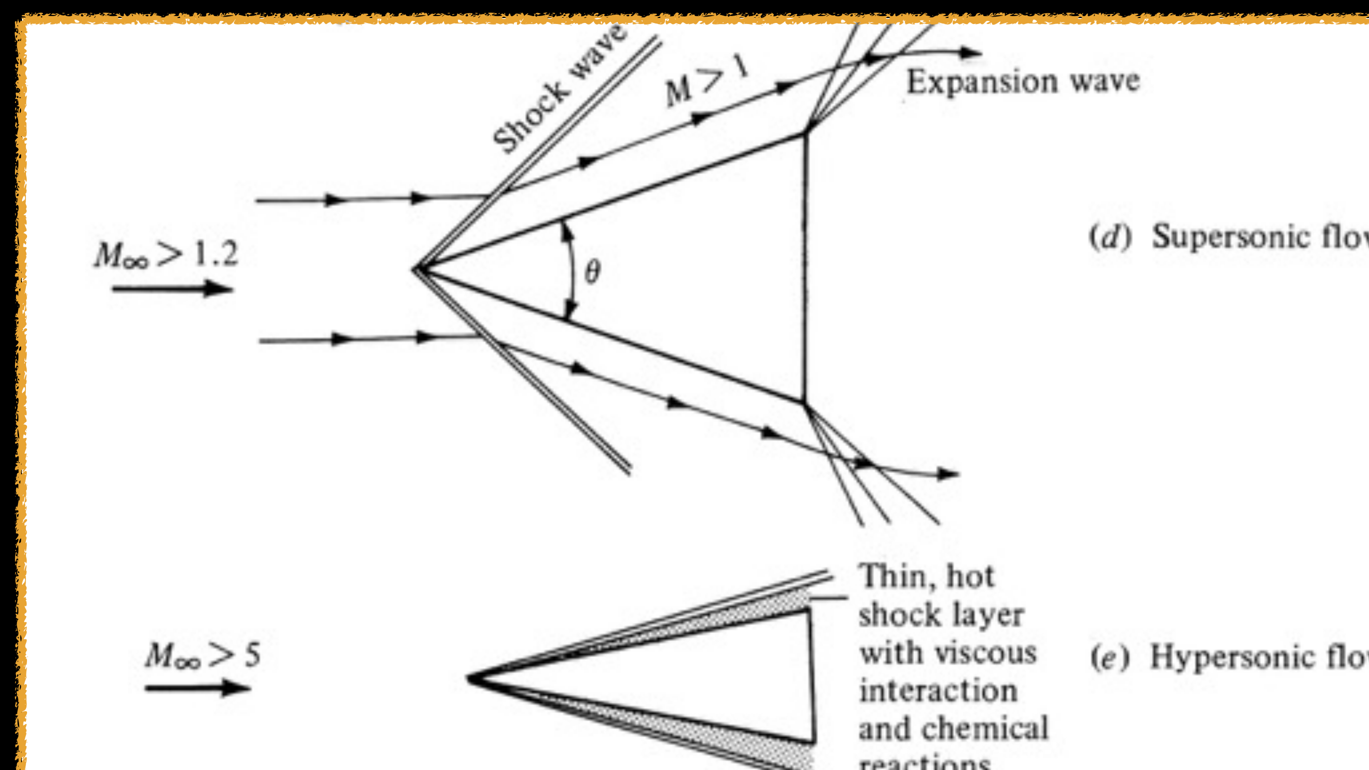
- *No inviscid flow theory can predict the aerodynamics of the above flows (viscous flows).*

Incompressible vs. Compressible Flows

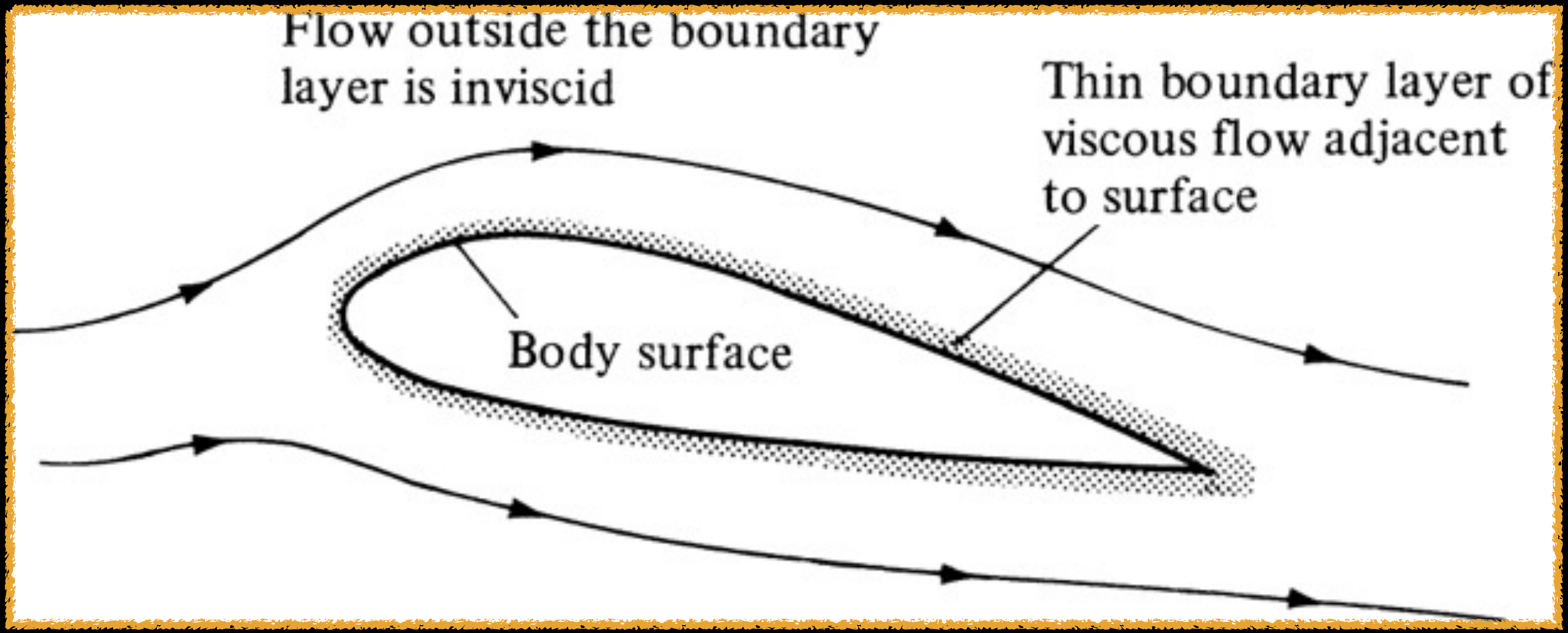
- *Flow in which density is constant: incompressible flow.*
- *Truly incompressible flow does not occur in nature. However, there are large number of flows in which the change in density is negligible.*
- *Such flows can be modeled as incompressible without any detrimental loss of accuracy.*
- *Flow in which density changes is called compressible flow.*

Mach Number Regimes



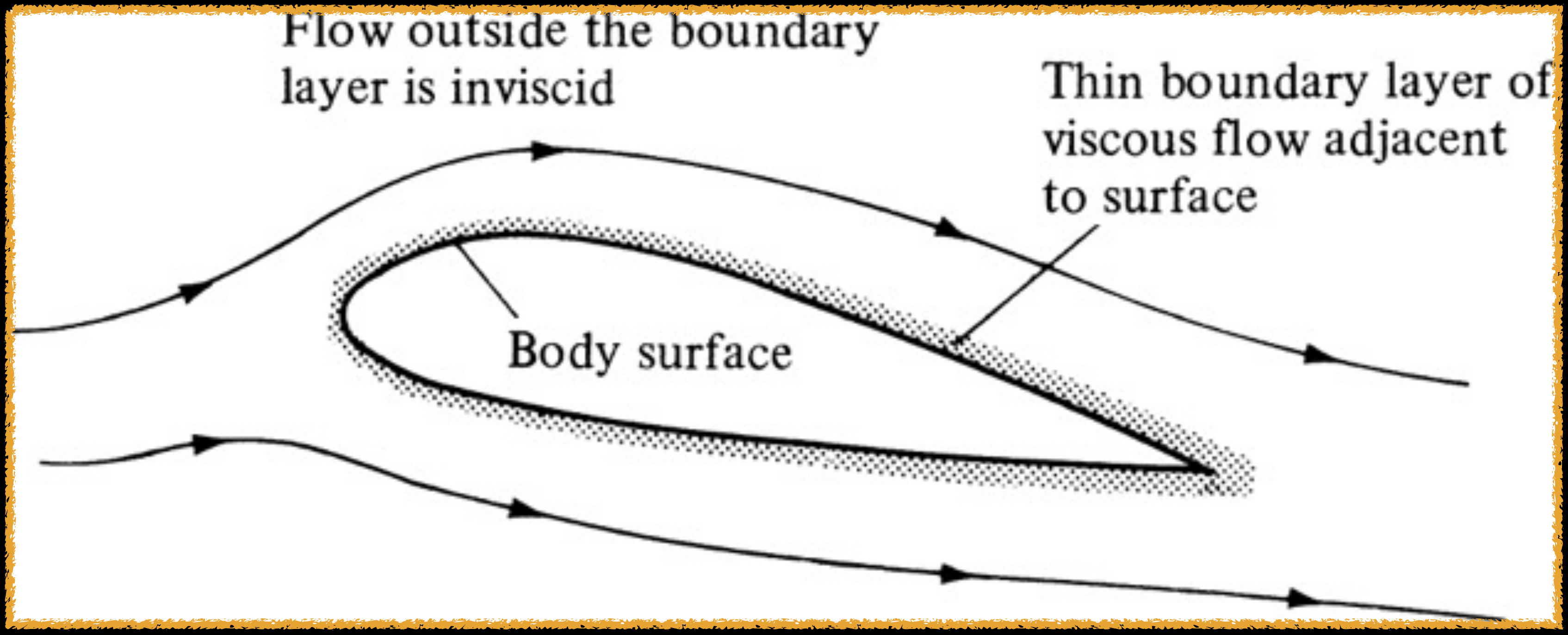


Viscous Flow: Boundary Layers



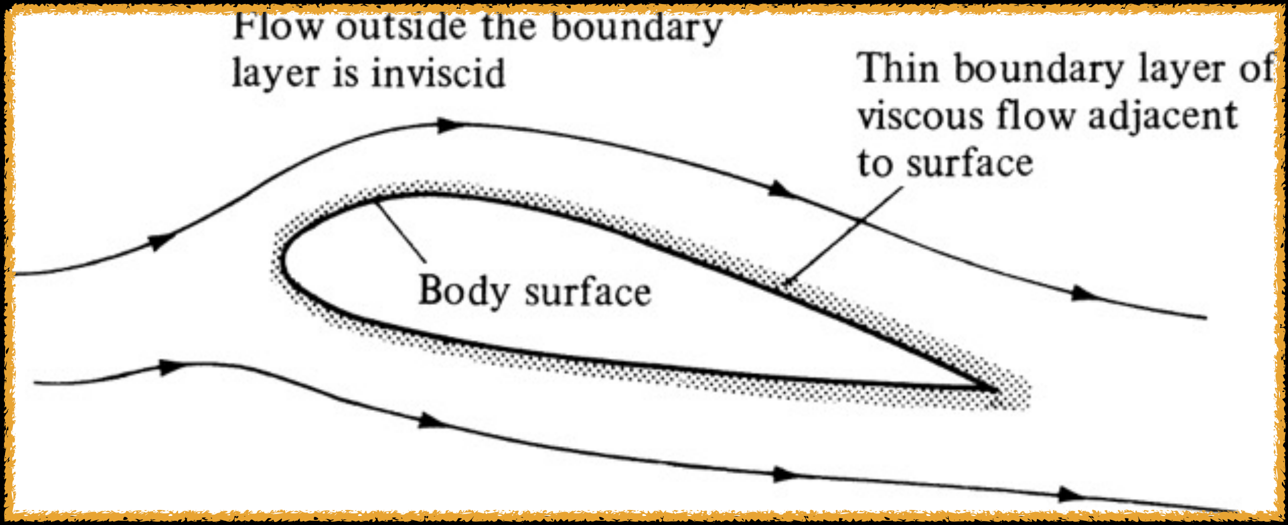
- *For the vast region of the flow field away from the body, velocity gradients are small, negligible friction.*
- *For the thin region adjacent to the surface, velocity gradients are large, substantial friction.*

Viscous Flow: Boundary Layers

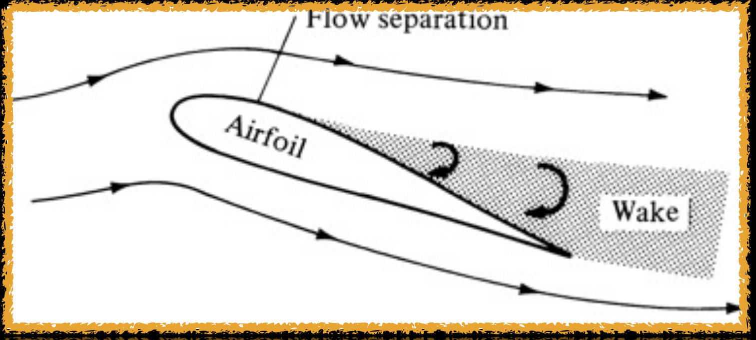


- *The thin viscous region adjacent to the body is called the boundary layer (Ludwig Prandtl, 1904).*
- *For most aerodynamics problems, the boundary layer is very thin compared to the extent of rest of the flow.*

Viscous Flow: Boundary Layers



- *Thin boundary layer - BUT what an effect it has!!*
  - *It is the source of friction drag on an aerodynamic body.*
  - *When the boundary layer separates from the surface, it dramatically alters pressure distribution resulting in large increase in drag - pressure drag.*



The Aerodynamic Coefficients

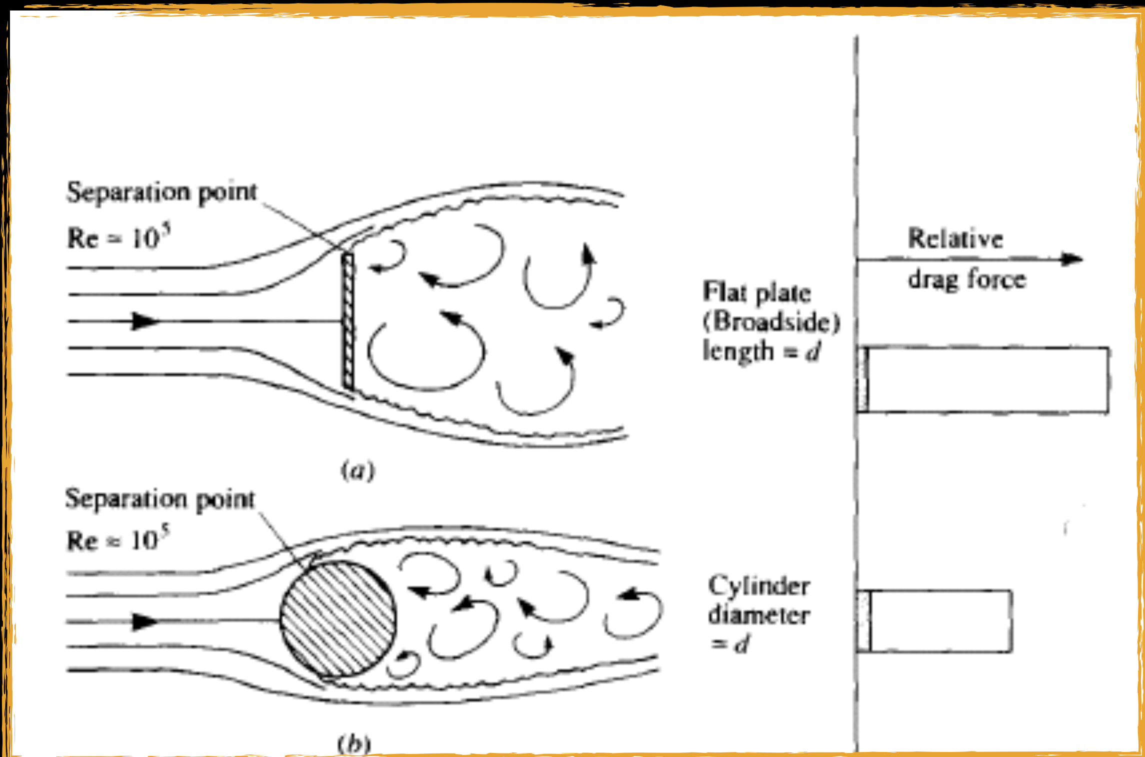
- *What are some typical drag coefficients for various aerodynamic configurations?*

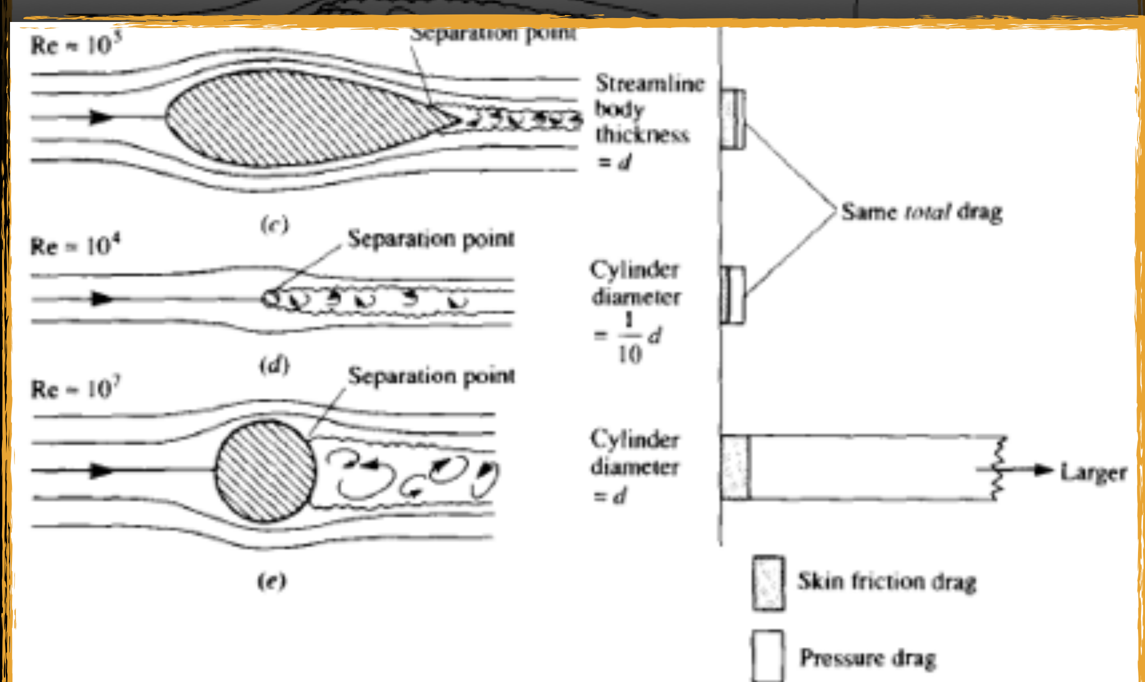
$$C_D = f(M, Re)$$

$$For\ incompressible\ flow,\ M \to 0\ because\ a\ is\ essentially\ \infty$$

- Therefore, drag coefficient for a fixed shape and orientation to the flow is only a function of *Re*.

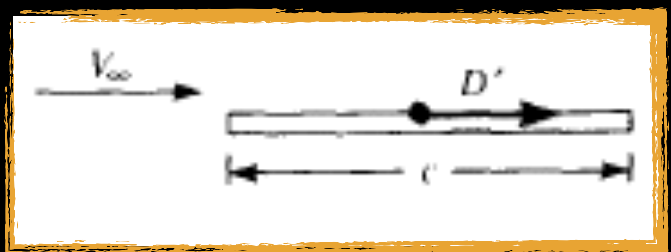
The Aerodynamic Coefficients



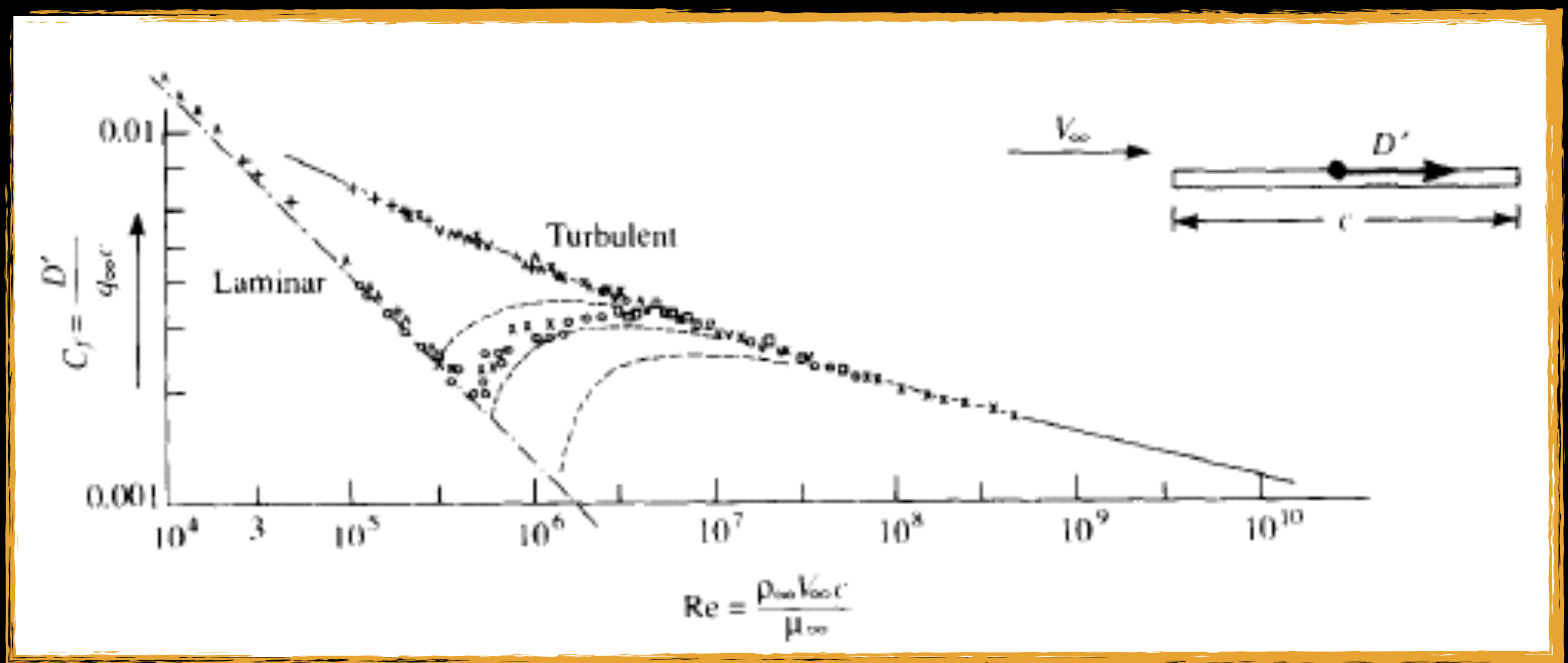


- *Blunt body: mostly pressure drag*
- *Pressure drag caused by flow separation - form drag.*
- *Streamlined: mostly friction drag*

Drag on a Flat Plate

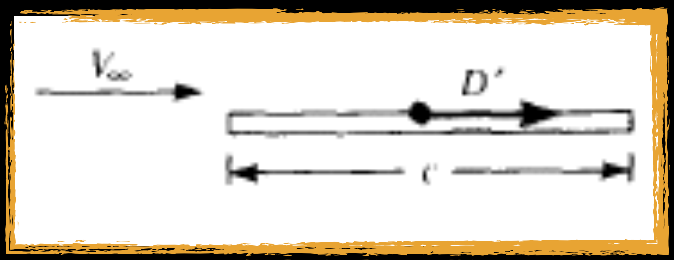


- *Drag is completely due to shear force.*
- *No pressure force in the drag direction.*



- *C_f is a strong function of Re.*
- *C_f is dependent on whether the flow is laminar or turbulent.*

NACA 63-210 Airfoil



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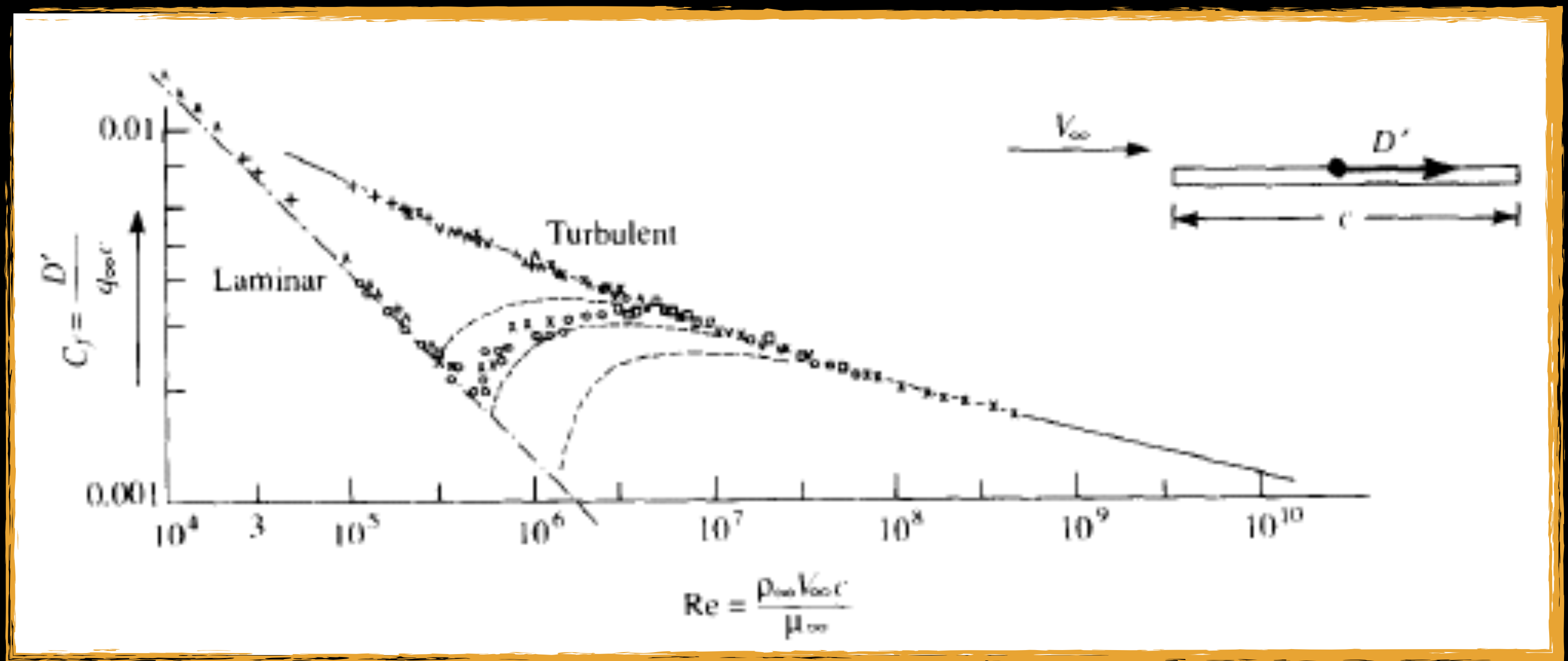

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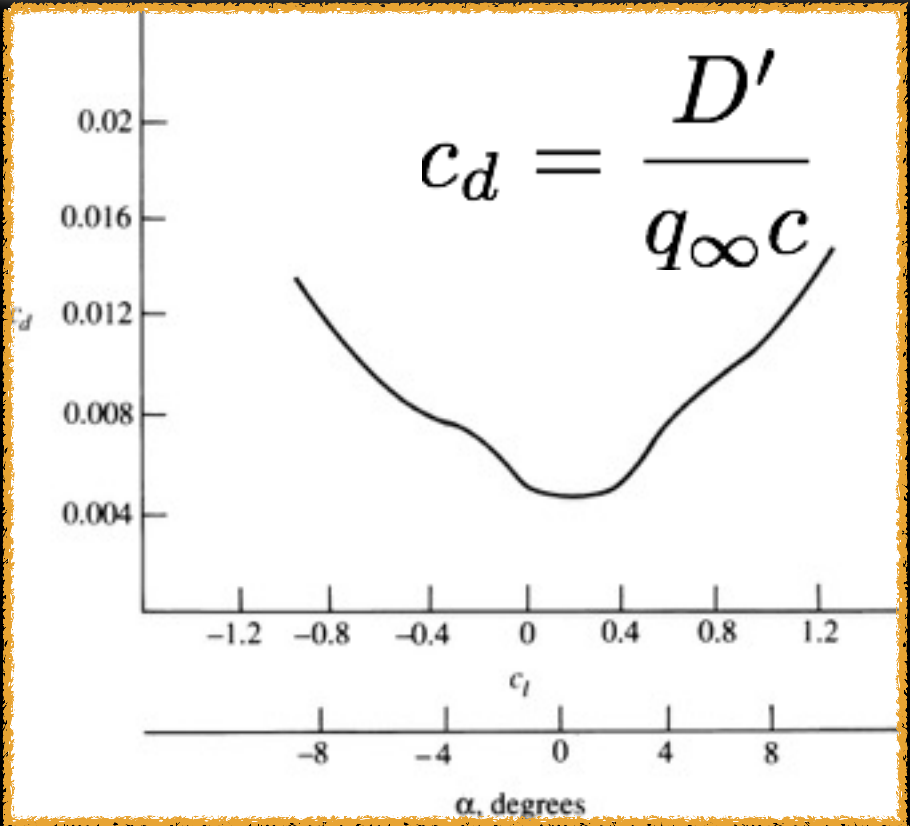
NACA 63-210 Airoil

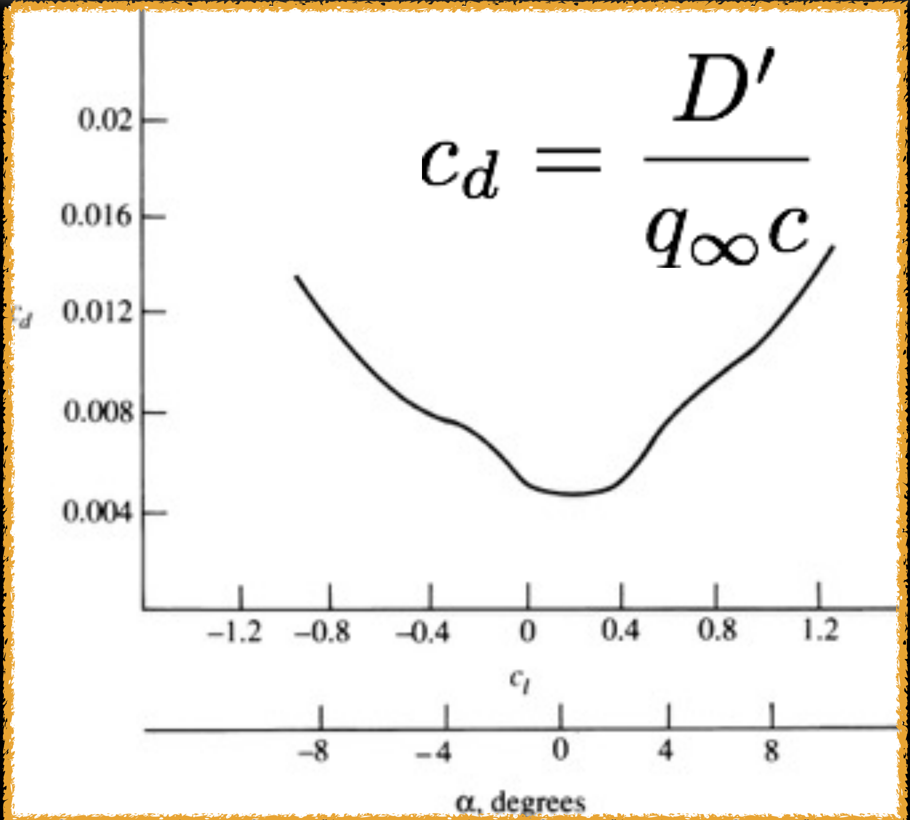
- *6 denotes the series and indicates that this family is designed for greater laminar flow than the Four- or Five-Digit Series.*
- *The second digit, 3, is the location of the minimum pressure in tenths of chord (0.3c).*
- *The third digit represents the lift coefficient.*
- *The final two digits specify the thickness in percentage of chord, 10%.*

NACA 63-210 Airoil



- *NACA 63-210 is classified as a laminar flow airfoil - it promotes laminar flow at small angles of attack.*
- *At higher angles of attack, it transitions to turbulent flow.*
- *The drag coefficient for laminar flow over the airfoil is of the order of 0.0045.*
- *Typical airfoil drag coefficients are between 0.004 - 0.006, mostly from skin friction.*
- *At higher angles of attack, form drag also contributes.*

NACA 63-210 Airoil



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