E80
Experimental Engineering

Fluid Measurement – The Wind Tunnel Lab

http://twistedsifter.com/2012/10/red-bull-stratos-space-jump-photos/

Outline

- Wind Tunnel Lab Objectives
- Why run wind tunnel experiments?
- How can we use WT data to help predict rocket flight path?
- WT Safety

Wind Tunnel Lab Objectives

1. Demonstrate the safe start-up and shut-down sequence for the wind tunnel.
2. Set and verify the wind speed in the wind tunnel.
3. Compare measured drag forces on standard shapes in a flow field with literature values.
4. Model and Measure the drag and lift forces on the rocket in various orientations in a flow field.
5. Calibrate the Pitot sensor in the rocket nose cone.

Flight modeling

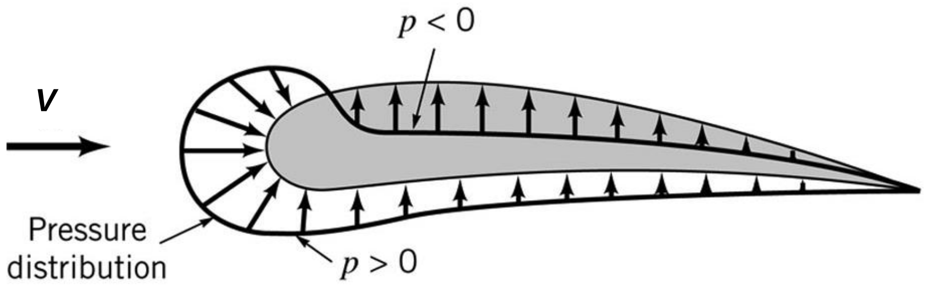
- What key forces dictate the flight trajectory?

Drag, Thrust, Lift, Gravity

Aerodynamic Forces

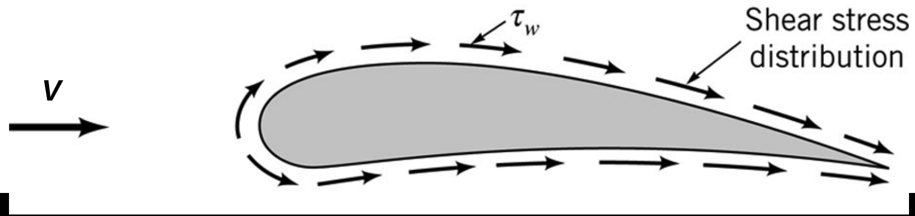
1. **Pressure**

   Acts perpendicular to surface



2. **Shear stress (friction)**

   Acts tangentially to surface



Why causes shear stress at surface?

- No-slip boundary condition

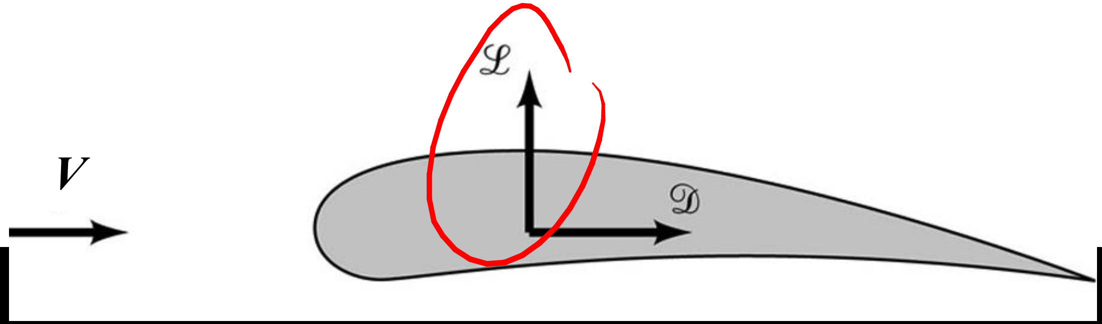
https://youtu.be/cUTkqZeiMow

Lift and Drag

The sum of pressure and shear stress is the *resultant force*. It is split into two components:

1. **Lift:** The component of resultant force that is ***perpendicular*** to the *incoming net velocity vector* (effective flow direction).

2. **Drag:** The component of resultant force that is ***parallel*** to the *incoming net velocity vector* (effective flow direction).



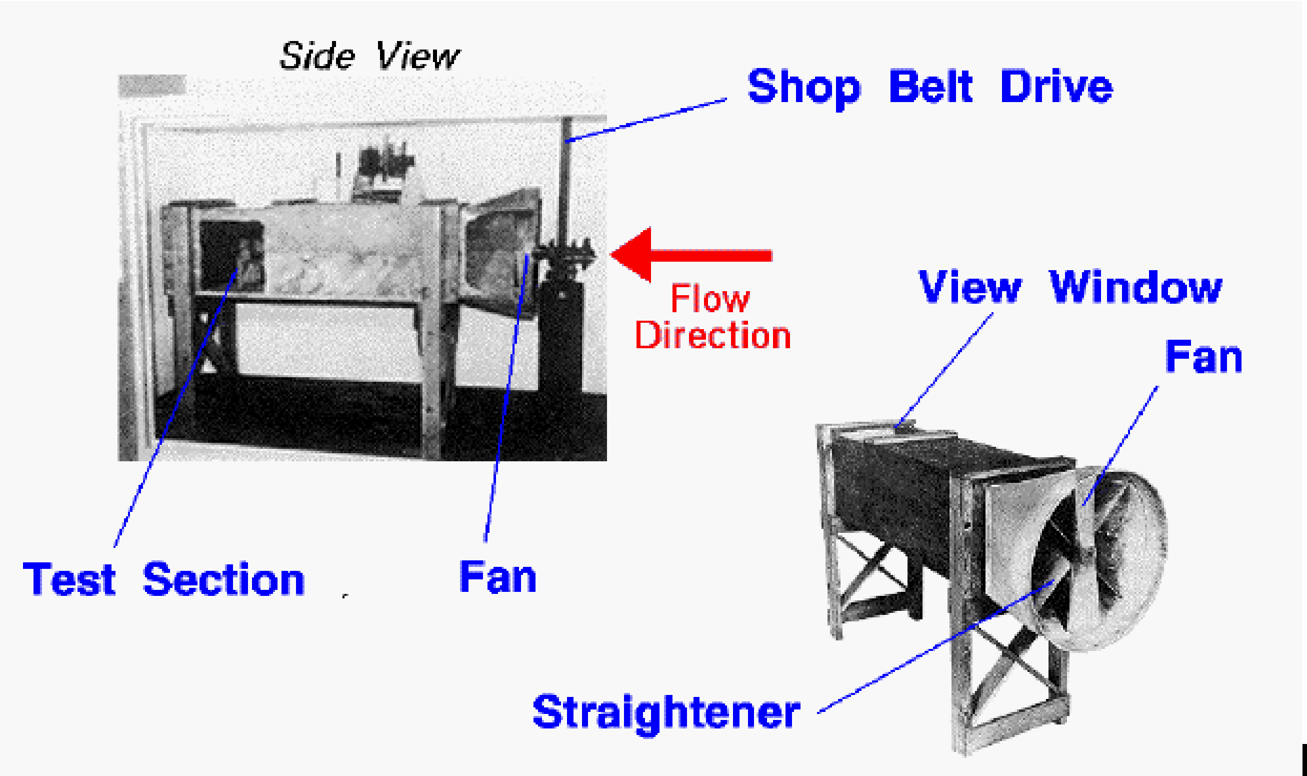
How are lift and drag modeled?

- **Option 1**: Full first-principles model (momentum balance)

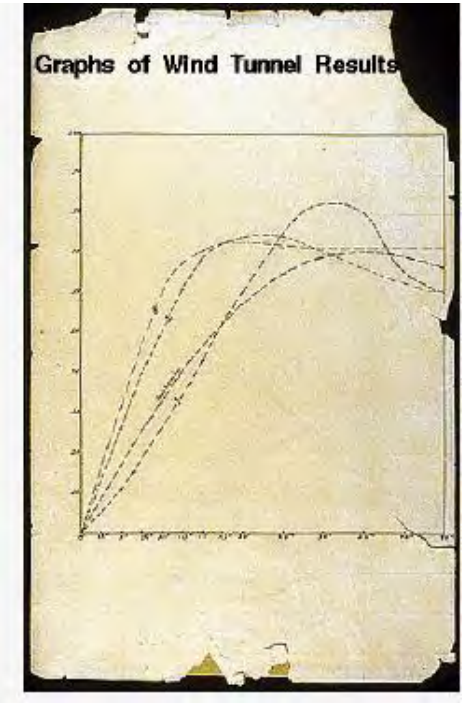
$$\underbrace{\frac{\partial}{\partial t}\rho\mathbf{v}}_{\text{rate of increase of momentum per unit volume}} = \underbrace{-[\nabla\cdot\rho\mathbf{v}\mathbf{v}]}_{\textbf{rate of momentum addition by convection per unit volume}} \underbrace{-\nabla p-[\nabla\cdot\boldsymbol{\tau}]}_{\text{rate of momentum addition by molecular transport per unit volume}} + \underbrace{\rho\mathbf{g}}_{\text{external force on fluid per unit volume}}$$

How are lift and drag ***really*** modeled?

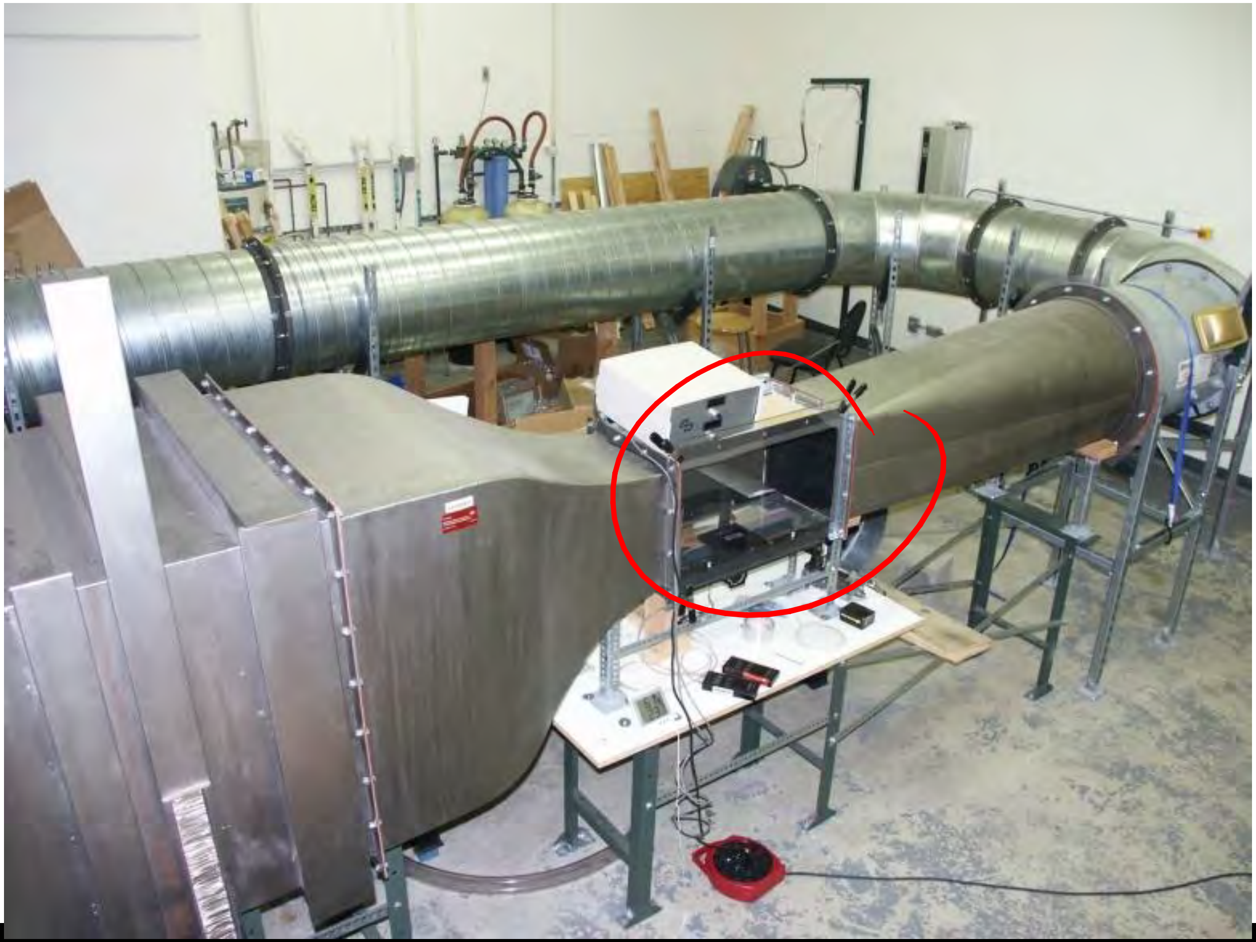
- **Option 2**: Empirical correlations developed in wind tunnels.



http://wright.nasa.gov/airplane/tunnel.html

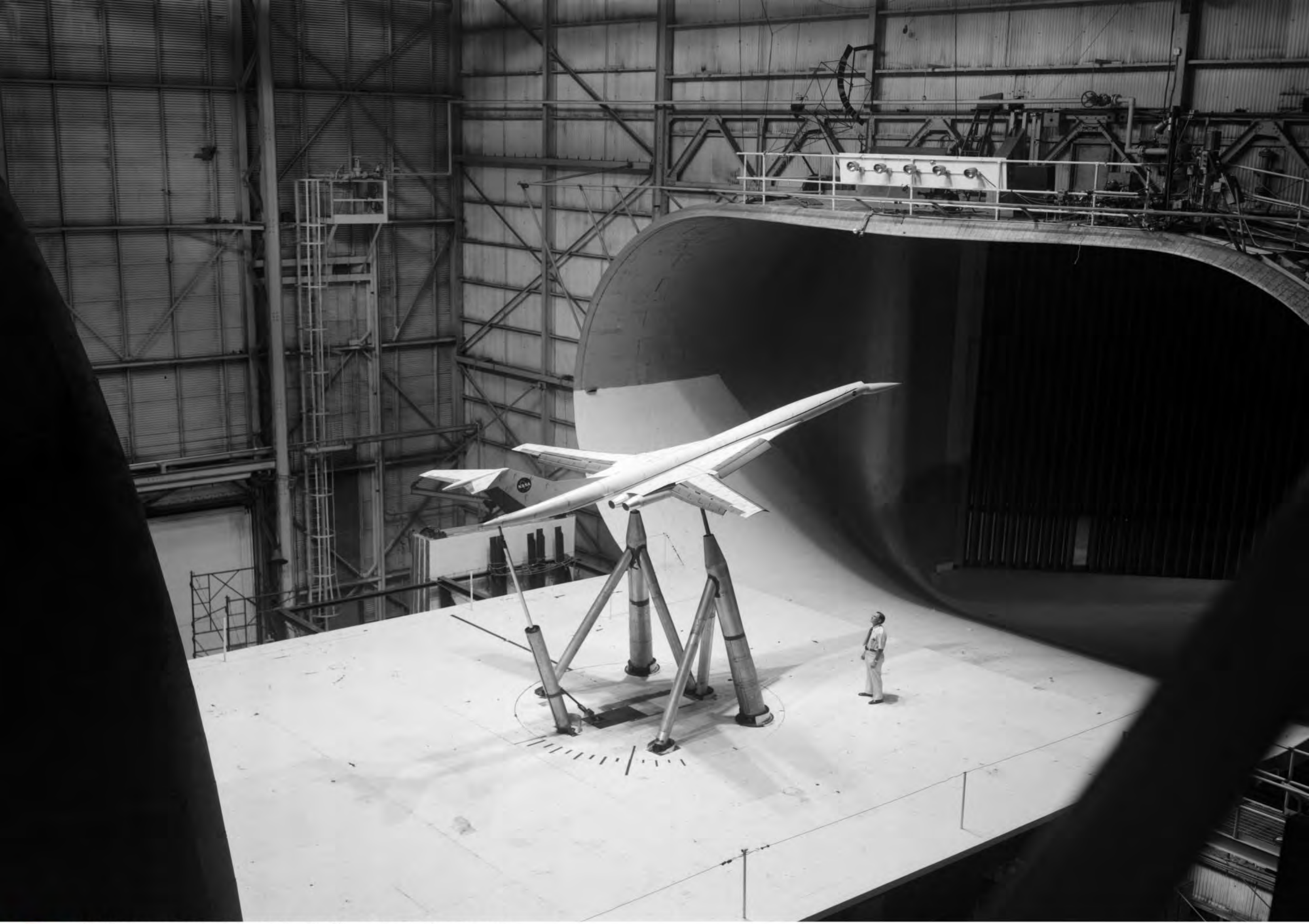


The HMC Wind Tunnel



Why wind tunnel experiments?

- Wind velocity has same effect as rocket velocity in stagnant air.
- Scale model testing.
- Develop correlations to predict performance under varying conditions.



SST model in Full Scale Tunnel
NASA Langley Research Center

7/1/1973

Image # EL-2001-00452

Wind Tunnel Variables

- **Independent Variables** (controls)
  - Fan RPM
  - Test object (e.g. sphere, cylinder, rocket model)
  - Angle of attack
- **Dependent Variables** (measured values)
  - Drag force on test object
  - Lift force on test object
  - Pitot tube digital manometer pressure output

What info do we want from WT experiments?

- “Resultant force” (can be decomposed into drag and lift forces) as a function of velocity and attack angle for full-size rocket under launch conditions.

What independent variables affect the resultant force?

$$F = f(\underset{\substack{\uparrow \\ \text{Characteristic} \\ \text{length}}}{L}, V, \mu, \rho)$$

E72!

Buckingham's Pi Theorem: Suppose that $Q_1, Q_2, \ldots, Q_n$ are n dimensional variables that are relevant to a given problem and that are related according to

$$F(Q_1, Q_2, \ldots, Q_n) = 0 \qquad \text{or equivalently} \qquad Q_1 = f(Q_2, \ldots, Q_n).$$

If k is the number of fundamental dimensions required to describe the n variables, then there exist $n - k$ independent variables $\Pi_1, \ldots, \Pi_{n-k}$, which are nondimensional groupings of the dimensional variables, and the functional relationship can be expressed as

$$\Psi(\Pi_1, \Pi_2, \ldots, \Pi_{n-k}) = 0 \qquad \text{or equivalently} \qquad \Pi_1 = \psi(\Pi_2, \ldots, \Pi_{n-k}).$$

$$\begin{array}{r l} \underline{5} & \text{variables } (L, V, \rho, \mu, F) \\ -\underline{3} & \text{fund. dim } (M, L, T) \\ \hline 2 & \end{array}$$

2 Key Dimensionless Numbers

1. Drag/Lift coefficient

$$C_D = \frac{F_D}{\underbrace{\boxed{\frac{1}{2}\rho V^2}}_{\text{dynamic pressure}} A} \qquad C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A}$$

2. Reynolds Number

$$Re = \frac{\rho V L}{\mu} = \frac{\text{inertial force}}{\text{viscous force}}$$

$$C_{D,L} = f(Re)$$

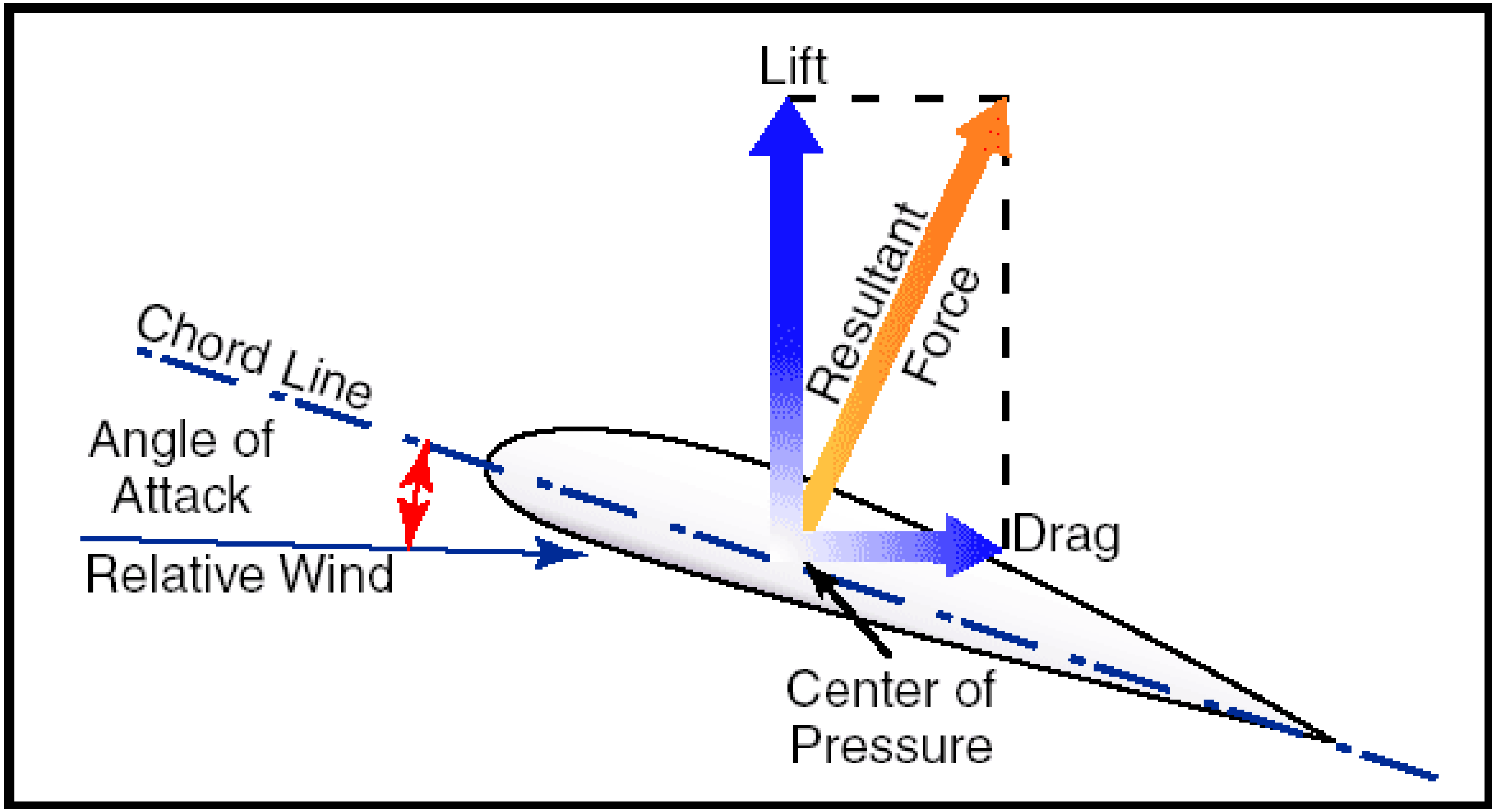
Complication #1: Reference Area

- Drag, lift coefficients are based on a reference area.

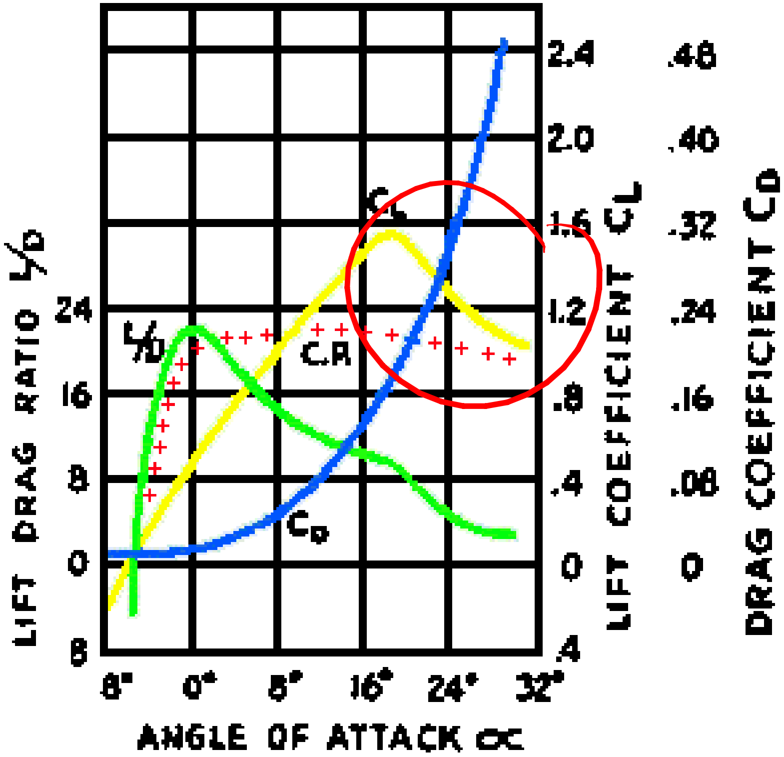
Complication #2: C_D, C_L = $f(Re)$

- Drag, lift coefficients aren’t constant during flight!

Complication #3: Angle of Attack



Complication #3: Angle of Attack



http://www.allstar.fiu.edu/aero/images/fig10.gif

A note from your lab instructions:

- "Note that the LVDTs measure the forces normal and parallel to the **wind direction**, and the lift and drag forces (on a rocket, not an airfoil) are normal and parallel to the **rocket direction**."

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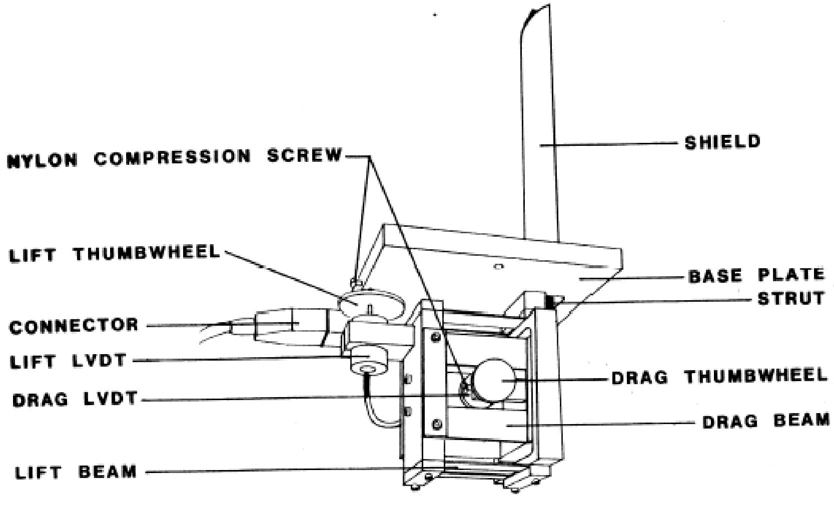
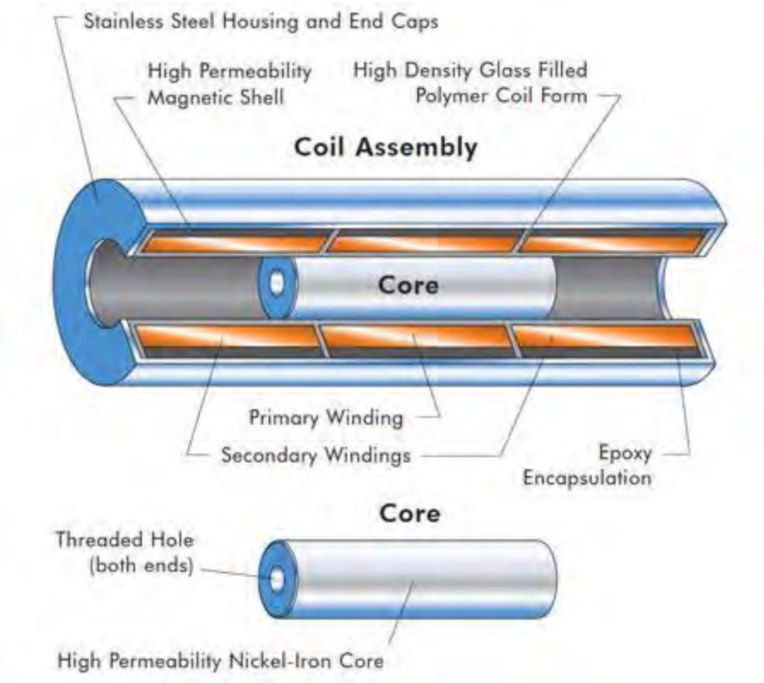
  - **Lift force on test object**
  - Pitot tube digital manometer pressure output

Drag and Lift Measurements

- Dynamometer + Linear Voltage Displacement Transducers (LVDTs)



DYNAMOMETER ASSEMBLY



http://www.macrosensors.com/images/tutorial_page_images/images/fig1.jpg

Wind Tunnel Variables

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Pitot-Static Tube

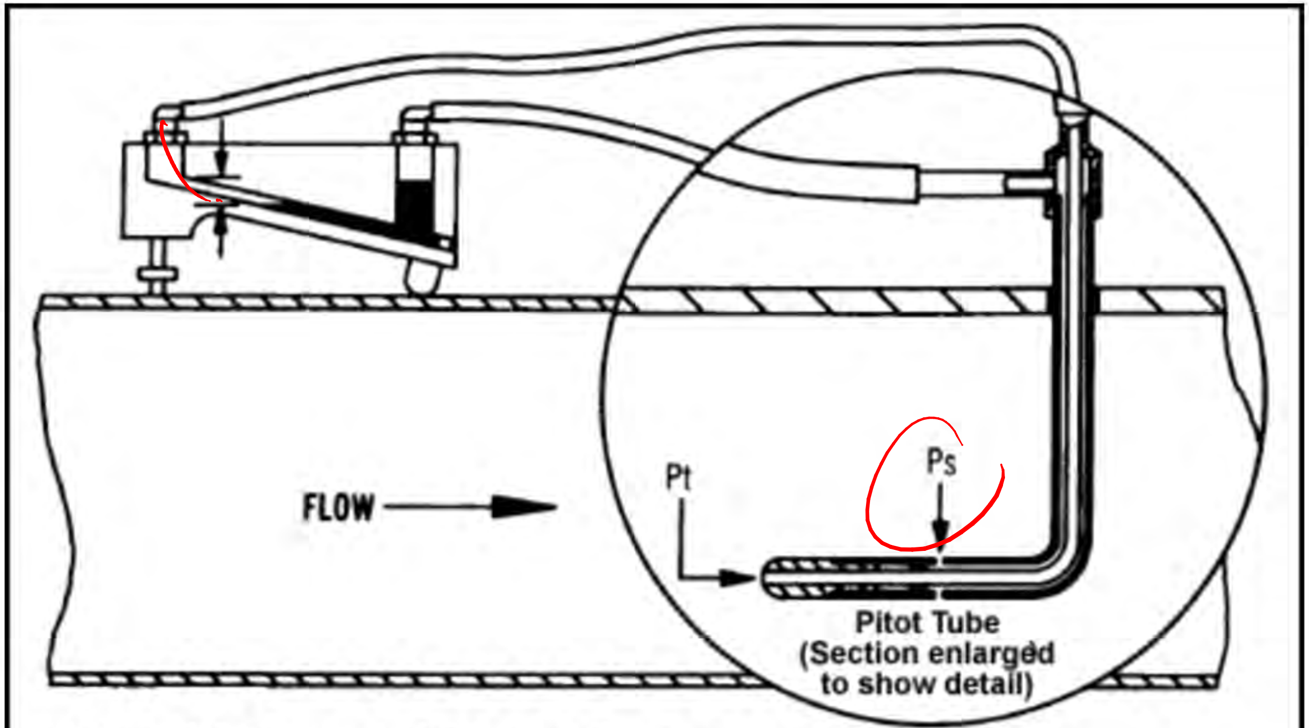


Fig.3 – Pitot Tube senses total and static pressure.
Manometer measures velocity pressure –
(Difference between total and static pressures).

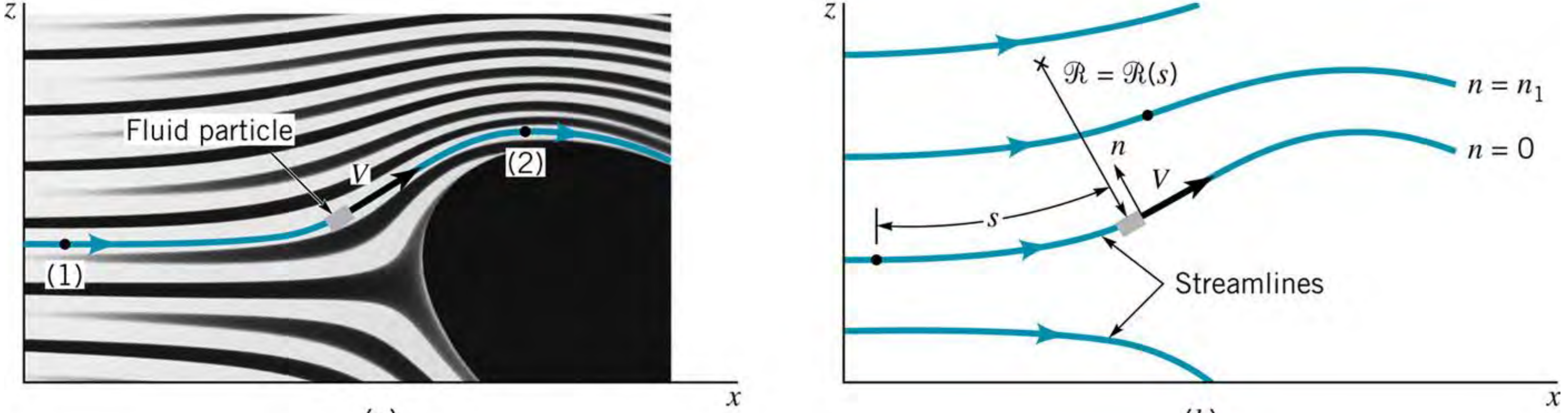
https://www.dwyer-inst.com/Products/AirVelocityIntroduction.cfm

Bernoulli Equation:
A Special Case of Conservation of Momentum

- **Along a streamline, for**:

Streamlines

- Lines tangential to velocity vectors throughout the flow field



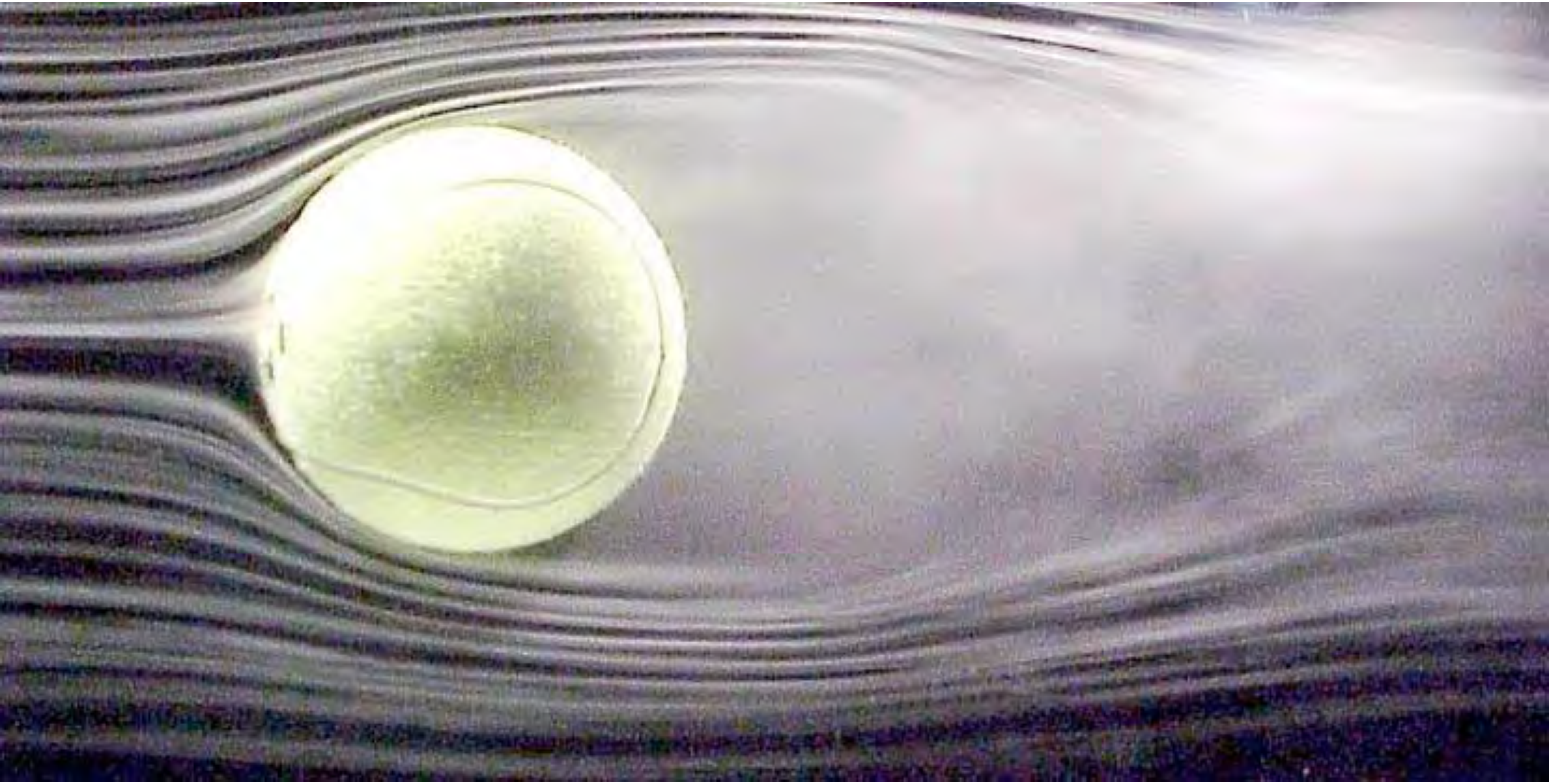
(a)

(b)

“Fundamentals of Fluid Mechanics,” Munson, Young, Okiishi, and Huebsch, 6th edition.

Streamlines around an airfoil

"Fundamentals of Fluid Mechanics," Munson, Young, Okiishi, and Huebsch, 6th edition.



http://www.nasa.gov/sites/default/files/thumbnails/image/edu_wind_tunnels_tennis_ball.jpg

Bernoulli Equation:
A Special Case of Conservation of Momentum

- **Along a streamline, for**:
  - Inviscid flow (negligible viscosity)
  - Steady flow
  - Incompressible (constant density) fluid
    - Reasonable for liquids
    - Can be applied to gases at sufficiently low velocity (Ma < 0.3)

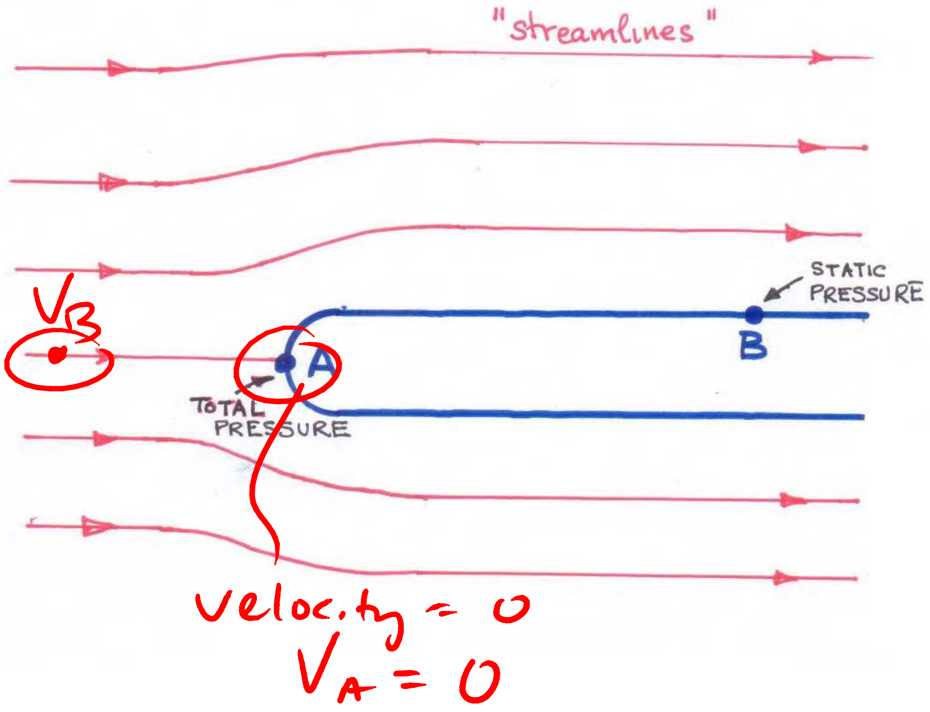
$Ma = \frac{V}{c}$

$\sim$ const T, p

For these conditions, the force balance (*F* = *ma*) gives:

$$\underbrace{p}_{\text{static pressure}} + \underbrace{\frac{1}{2}\rho V^2}_{\text{dynamic pressure}} + \rho g z = \text{constant along streamline}$$

Pitot-Static Tube



$$p_B + \frac{1}{2}\rho V_B^2 + \cancel{\rho g z_B}$$

$$= p_A + \cancelto{0}{\frac{1}{2}\rho V_A^2} + \cancel{\rho g z_A}$$

$$\boxed{V_B = \sqrt{\frac{2(p_A - p_B)}{\rho}}}$$

A manometer on your rocket?

- Maybe not . . ..

MX053DP differential pressure sensor
http://www.digikey.com/product-detail/en/MPX53DP/MPX53DP-ND/951812

Safety

- Follow the Dress Code for E80 Lab
- Never turn the FAN on without
  - Checking to see that no loose objects are in the test chamber
  - Securing the test chamber cover plate
  - Making sure all test personnel are at a safe distance from the wind tunnel itself (at least 24” in any direction)
  - Making sure the vent is clear
  - Making sure the article under test is securely fastened inside the test chamber
- Do not run the fan at speeds higher than the posted limit.