The Wind Tunnel

FLUID MEASUREMENTS

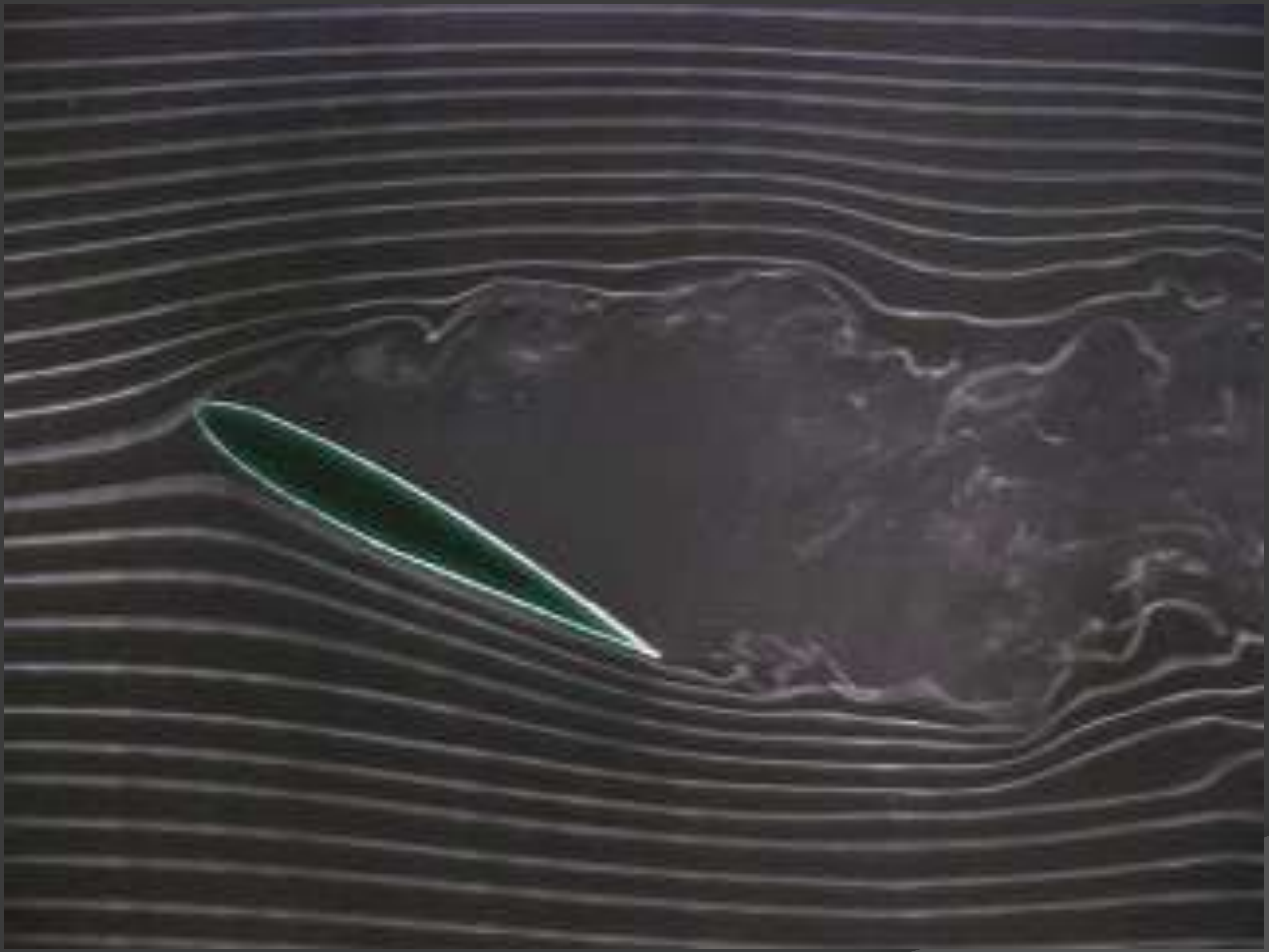
Cayley

http://www.ctie.monash.edu.au/hargrave/images/cayley.mov

Cayley’s Whirling Arm

- Cayley did this in 1804, and built and flew unmanned glider with wing area of 200 sq. ft.
- What was Cayley trying to measure?
- Any issues with his whirling arm? Does it mimic what a real glider “sees”, in terms of fluid flow?

Airfoil in smoke tunnel



What about cars in tunnels?

http://stopbuyingrotas.files.wordpress.com/2008/10/voltex.jpg

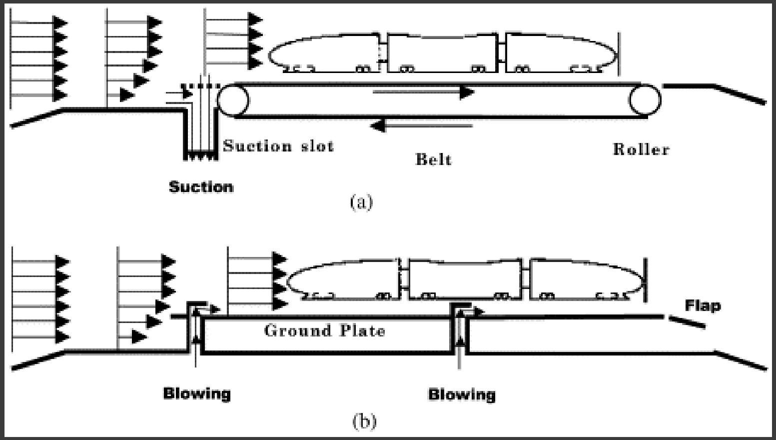
Car testing

- What needs to be there to make it like a real car driving on a road?
- What kinds of things would you want to measure?
- Any comments about the tunnel itself?

Rolling Road Wind Tunnel

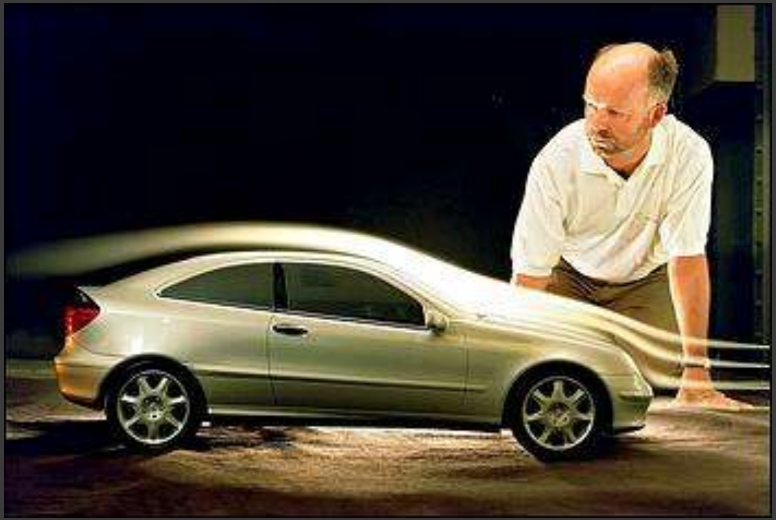
http://www.wired.com/cars/coolwheels/magazine/15-10/pl_motor

Other ways to match fluid flow between bottom of car and road



http://ars.els-cdn.com/content/image/1-s2.0-S0167610501001076-gr1.gif
http://www.testslate.com/casestudies_windshear.html

Less expensive to do scaled models



- What do we have to do in order to test scaled models?
  - Geometry scales
  - Paths of fluid particles look the same, velocity of fluid particles scales
  - Forces scale
- Called **similarity** (geometric, kinematic, dynamic)
  - More in a bit…

Mars Curiosity parachute

http://www.cleveland.com/science/index.ssf/2012/07/wind_tunnel_testing_at_clevela.html
http://www.super-collider.com/styrofoam/wp-content/uploads/2012/08/parachute.jpg

Other examples

http://images.motorcycle-usa.com/PhotoGallerys/wind-tunnel-02.jpg
http://history.nasa.gov/SP-440/ch4-3.htm

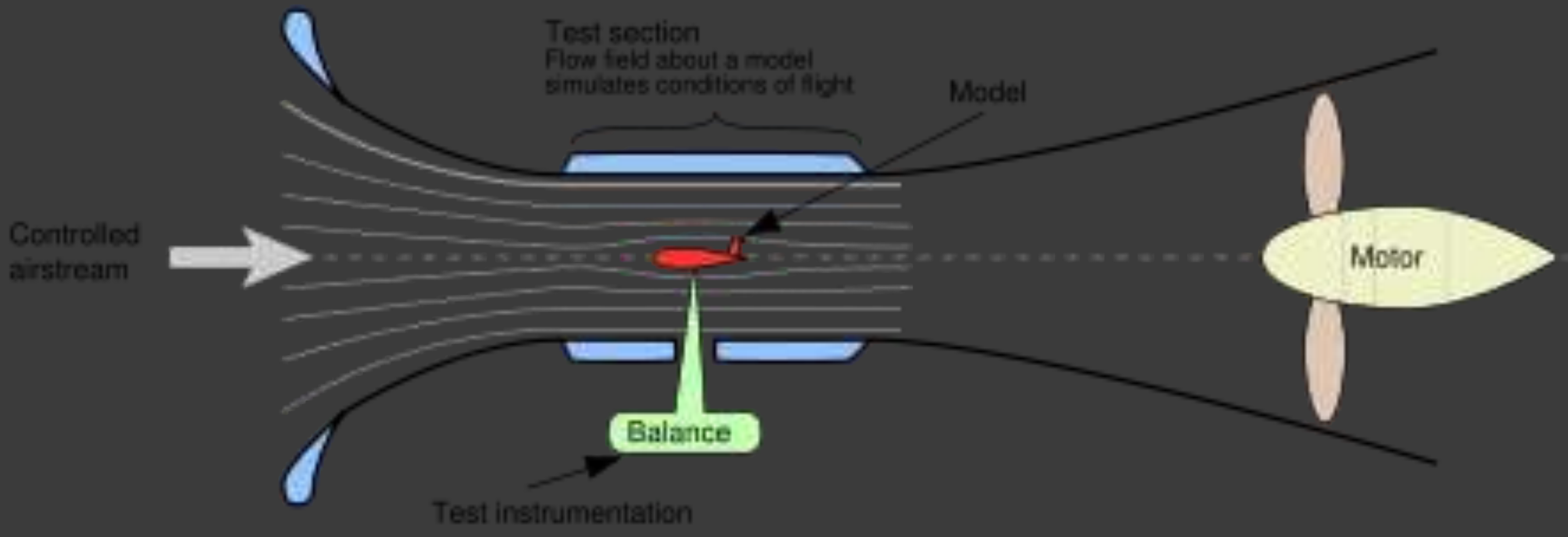
Wind Tunnel

- Ground-based experimental facility designed to produce flow of gases (often air) to simulate natural flows occurring around a vehicle or other object
- Commonly used for flight vehicles (airplanes, jets, rockets, space vehicles)
- Many different types of tunnels, depending on application (low-speed, supersonic, hypersonic, ice testing, spin testing)

Why do we need experimental data?

- Can’t we just do computational fluid dynamics to solve for everything we need?
  - CFD doesn’t work well for everything
    - Flow separation, some fluid-structures interactions
  - In the past, CFD took too long to run
  - For flight vehicles, it’s a really good idea to get wind tunnel data before you actually fly
    - “Tunnel tests first, free-flight tests later, is the proper order of things.” –NASA (from “Wind Tunnels of NASA”)
    - “We validate the designs,” Wendy Lacy, Boeing test engineer

Low-speed wind tunnel schematic



http://www.thefullwiki.org/Subsonic_and_transonic_wind_tunnel

HMC Wind Tunnel

Prof. Jenn Rossmann's tunnel

1' x 1' test section, 140 mph

Note: open door to outside before operating!

Low-speed wind tunnel

- M = Mach number = velocity/speed of sound
- For M < 0.3, density can be taken as constant (incompressible fluid)
- M=0.3 is about 230 mph at sea level
- At steady-state operation, assuming uniform velocity across cross-section, conservation of mass is:
- $\rho_1 A_1 V_1 = \rho_2 A_2 V_2 = \dot{m}$ (mass flow rate)
- $V_2 = \frac{A_1}{A_2} V_1$

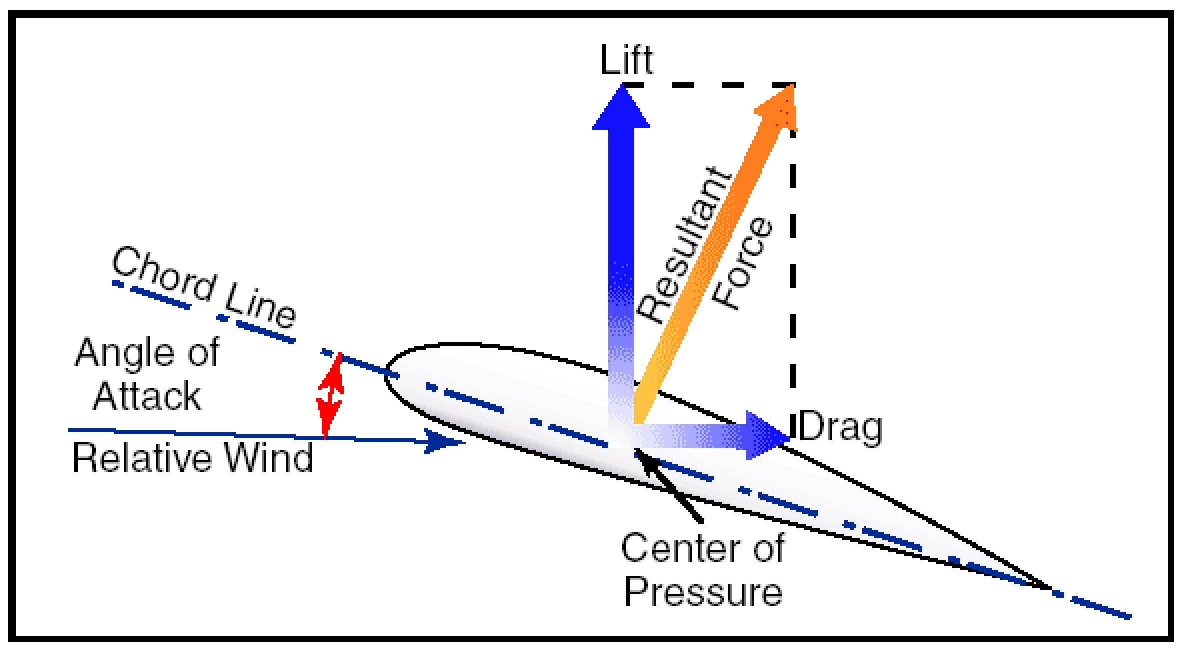
Bernoulli's Eqn

- $P_1 + \rho \frac{{V_1}^2}{2} = P_2 + \rho \frac{{V_2}^2}{2}$ = constant along a streamline
  - Assumed friction is negligible, gravity negligible, steady flow, incompressible fluid, flow is along a streamline
- We can derive this from conservation of momentum or conservation of energy

Operation of wind tunnel

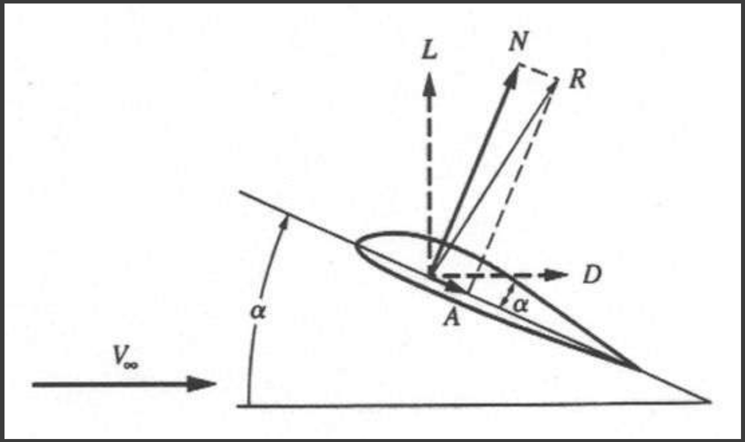
- Although we need to be careful when using Bernoulli's eqn because of restrictive assumptions, we can use it to gain some insight
- $V_2 = \sqrt{\frac{2(P_1 - P_2)}{\rho(1-(\frac{A_2}{A_1})^2)}}$
- Area ratio of wind tunnel is known, so we vary the pressure difference to get our desired test section velocity

Forces: Lift and Drag



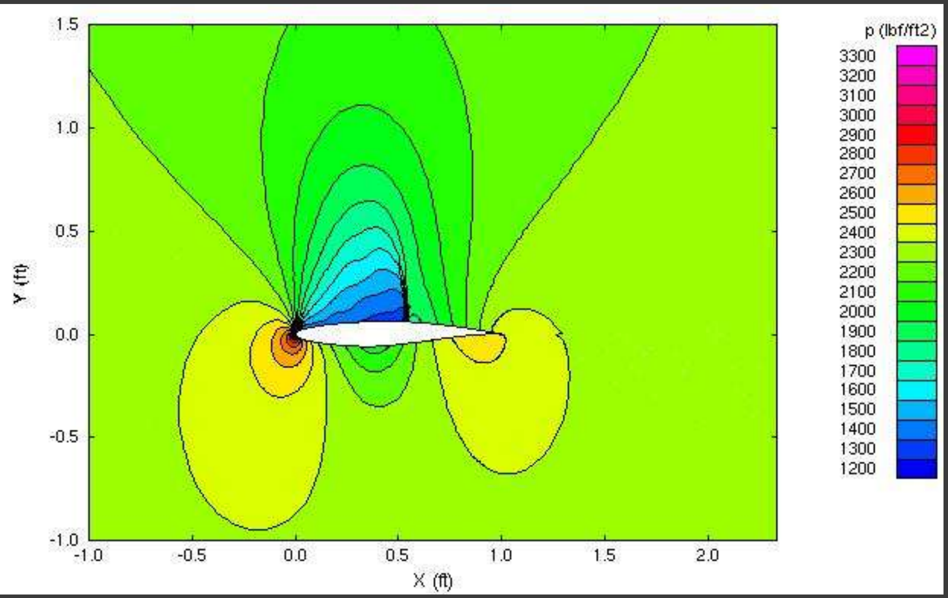
http://www.free-online-private-pilot-ground-school.com/aerodynamics.html

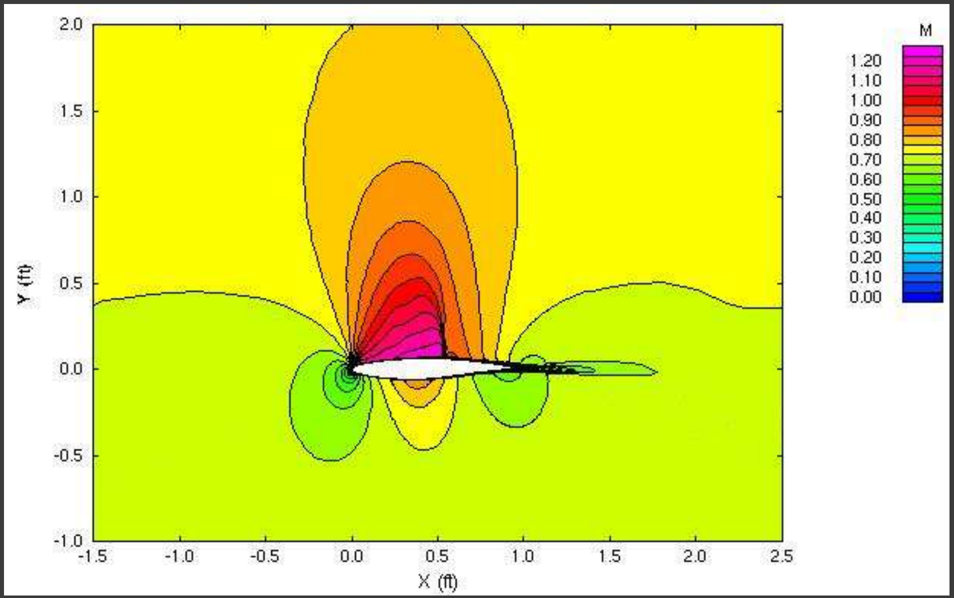
Also Normal and Axial Forces



- Lift Force perpendicular to relative wind
- Normal Force perpendicular to some body axis
- In some literature, Normal Force is called the "Lift Force" (NOTE: the E80 web site is one of these)

Pressure and velocity on an airfoil





Pressure contours **Mach number contours**

http://www.grc.nasa.gov/WWW/wind/valid/raetaf/raetaf04/raetaf04.html

Pressure sensors

Absolute pressure sensor

Differential pressure sensor

http://sigma.octopart.com/8927755/image/Freescale-Semiconductor-MPXV4006GC7U.jpg
http://twarm.com/commerce/product_info.php?cPath=158_164&products_id=3391&sid=98

Pressure sensors

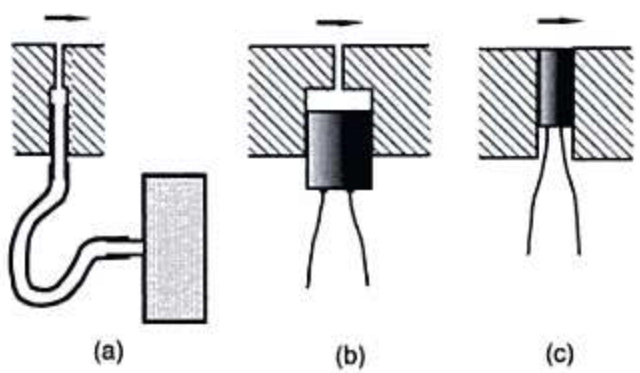


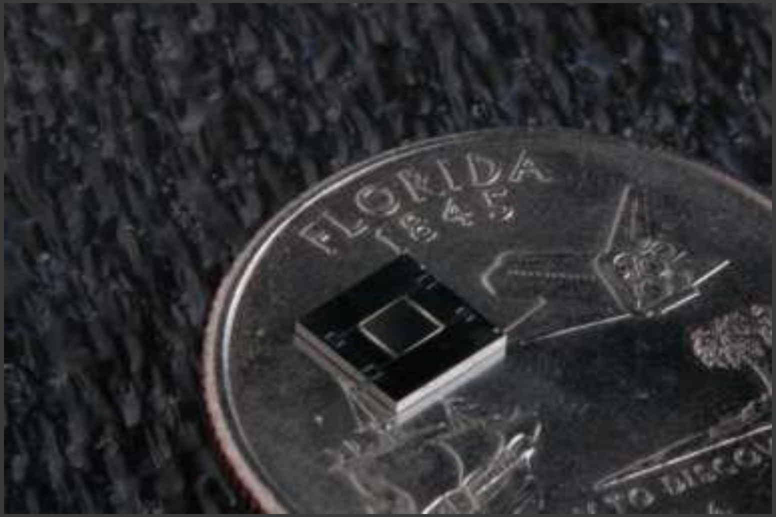
Figure 8.6. Various ways of connecting pressure transducers for the measurement of wall pressure: (a) remote connection, (b) cavity mounting, and (c) fluch mounting.

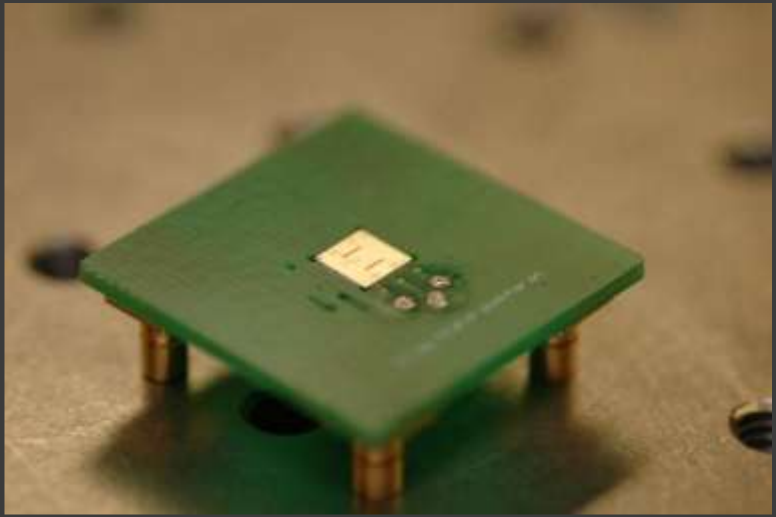
From “Measurement in Fluid Mechanics” by Stavros Tavoularis
http://www.althensensors.com/public/media/Produktbilder/1a_Druckmesstechnik/MP40-drucksensor-400x260.png

Wall Shear Stress

- Wall shear stress (due to frictional forces) contributes to lift and drag
- Common to measure pressure distribution over a surface in a wind tunnel
  - Pressure transducers
- Less common to measure wall shear stress
  - Floating MEMS sensors, optical coatings
- Integrate surface pressure and shear stress to calculate resultant force

Wall shear stress sensor





http://www.nasa.gov/topics/aeronautics/features/shear_stress.html

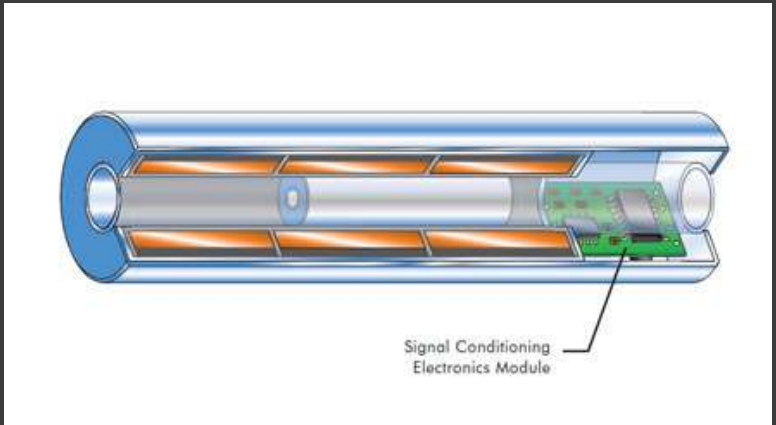
Force Balance: the heart of a wind tunnel

- Rather than measuring pressure and wall shear stress and then integrating, we measure forces on our model (good balances measure moments as well)
- Instruments often measure a deflection or strain, produce a voltage, and relate that to force
  - Strain gages
  - Linear variable differential transformers (LVDT)

Force Coefficients

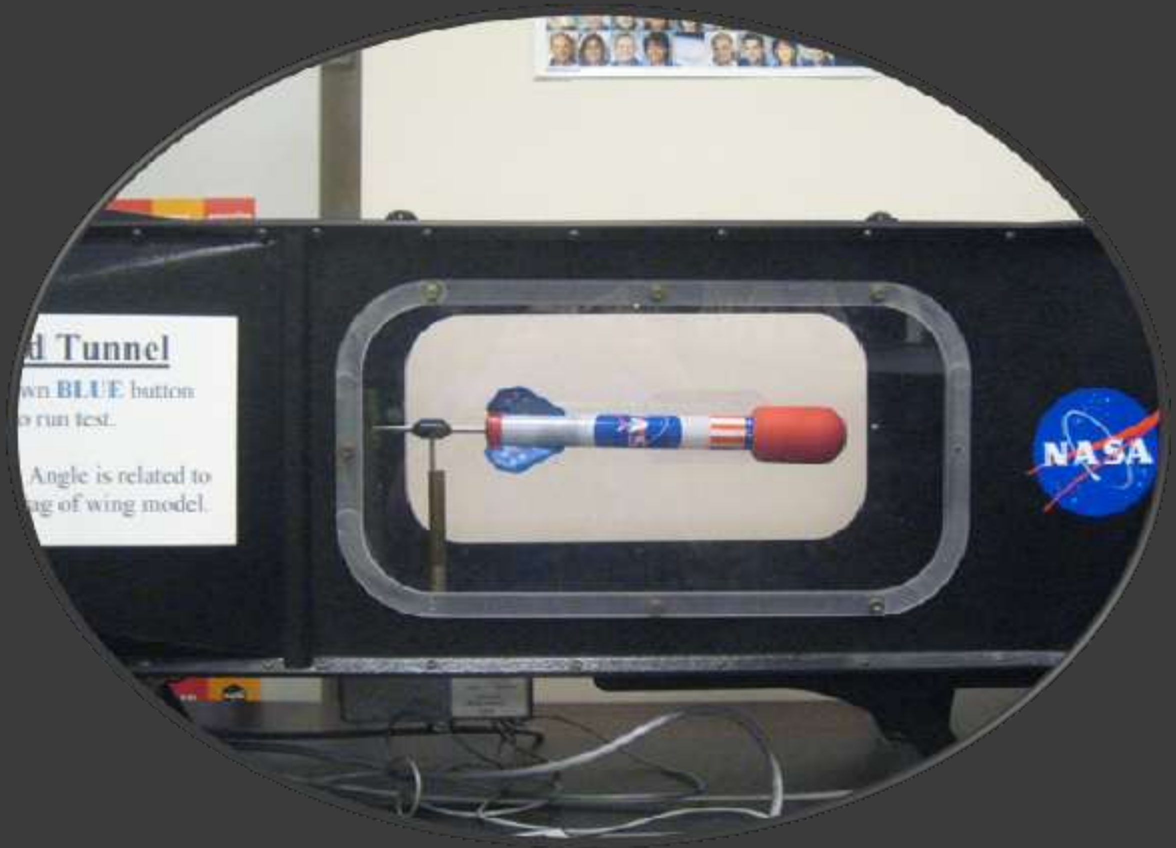
- F_L = lift = $\frac{1}{2}\rho V^2 A C_L$
  - Where $\rho = \text{free stream density}$
    $V = \text{free stream velocity}$
    A = reference area
    C_L = lift coefficient
- F_D = drag = $\frac{1}{2}\rho V^2 A C_D$
  - Where C_D = drag coefficient
- We're going to experimentally determine drag coefficients as part of this lab
  - Measure drag force
  - Measure flow velocity

LVDT



http://www.macrosensors.com/lvdt_tutorial.html
http://www.singer-instruments.com/sites/default/files/documents/products/Low-Range-Force-Sensors-F-and-FD-series.pdf

Sting Balance



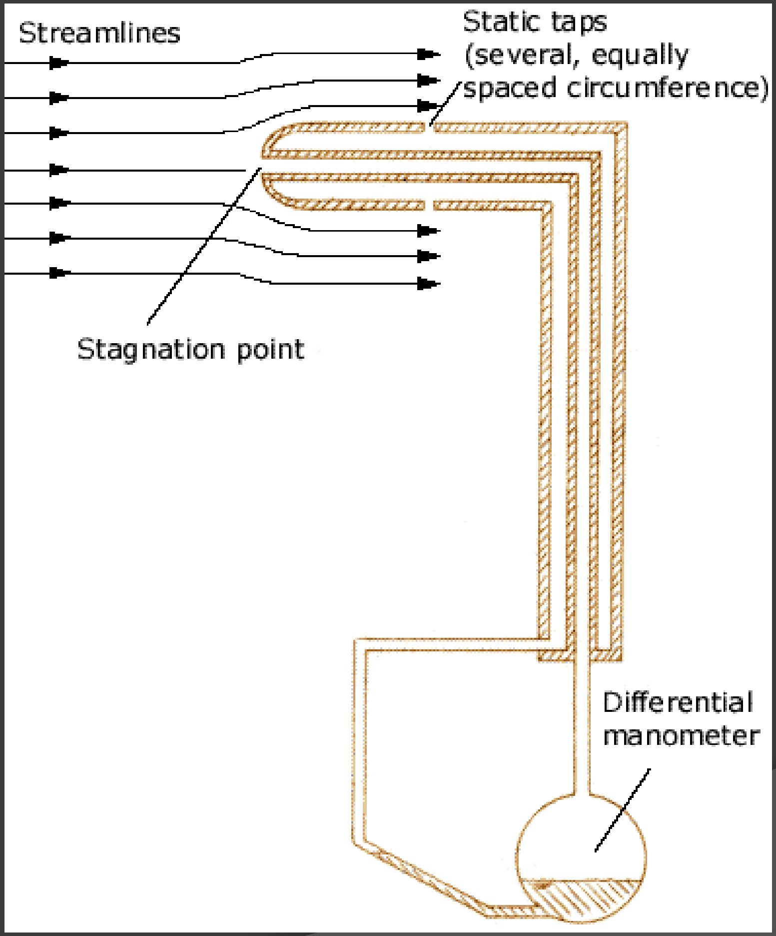
- Note: Tare Forces (from the Arabic "tarha" meaning “deduction”) will act on the sting
- Random historical fact: early models were suspended from thin wires; unfortunately, drag on the wires sometimes exceeded model drag by a factor of 10!

http://www.grc.nasa.gov/WWW/k-12/rocket/dragdat.html

Velocity Measurements

- Pitot-static tube
- MPX53DP differential pressure sensor

- Piezoresistive pressure sensor. Pressure causes resistance change in silicon diaphragm, output as voltage



http://twarm.com/commerce/product_info.php?cPath=158_164&products_id=3391&sid=98

Pitot-static measurement

- Stagnation, or total, pressure, P_0. Pressure of the gas when the fluid velocity is zero.
- Static pressure, P —what you probably think of when you think of pressure
- $V = \sqrt{\frac{2(P_0 - P)}{\rho}}$ (this is Bernoulli's eqn again)
- Our differential pressure sensor measures the difference between stagnation and static P
  - What kind of pressure sensor shall we use?
- Where on the rocket will we get a stagnation point? Where on the rocket should we measure static pressure?

Pitot Tube Static Port

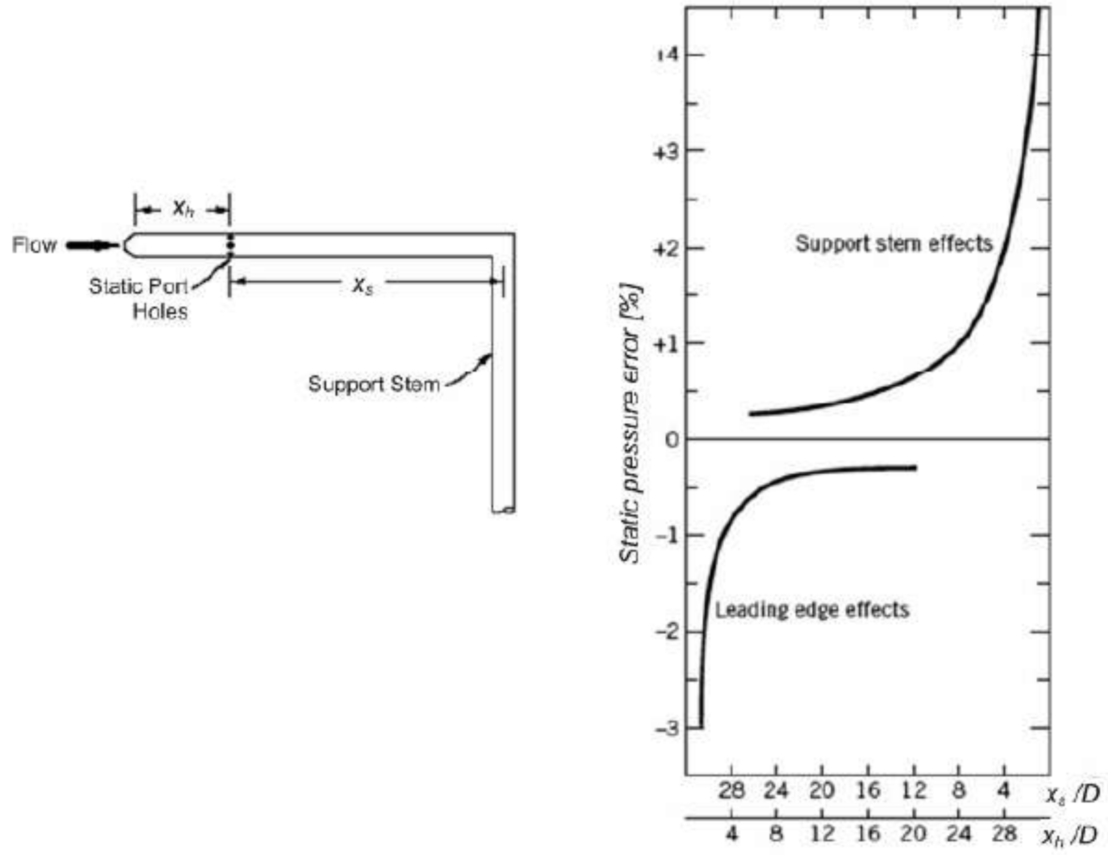


Figure 4. Static pressure errors due to static port hole placement.

http://search.asee.org/search/fetch;jsessionid=459m5p7k76jr7?url=file%3A%2F%2Flocalhost%2FE%3A%2Fsearch%2Fconference%2F17%2FAC%25202008Full522.pdf&index=conference_papers&space=129746797203605791716676178&type=application%2Fpdf&charset=

Similarity and Dimensional Analysis

- Similarity: How to make sure our scale models in the tunnel simulate our real-life vehicle
  - geometric, kinematic, and dynamic
- Dimensional Analysis: Method for reducing the number and complexity of experimental variables that affect a given physical phenomenon
  - Helps us be more efficient, keeps us from running redundant experiments, helps with insight
  - Will explain where our force coefficients came from

Similarity

- Geometric similarity: all body dimensions in all three coordinates have the same linear scale ratio
- Kinematic similarity: same length scale ratio and same time scale ratio (this means the velocity scale ratio will be the same)
- Dynamic similarity: same length scale, time scale, and force (or mass) scale ratios
  - Means that forces are in the same ratio and have equivalent directions between the real thing and scaled model

Similarity

- To get complete similarity for a general flow field, we need to have geometric, kinematic, and dynamic similarity
- Reynolds number, Re, governs this for the type of fluid flow we are interested in for E80
  - $Re = \frac{\rho V L}{\mu}$ (dimensionless)
  - L = characteristic length scale
  - μ =fluid viscosity

Dimensional Analysis

- We want to determine drag force on our sphere
- We think that F_D=f(length-scale, velocity, density, viscosity)
  - Why both density and viscosity? Can change fluid, also can change temperature
- We could run experiments that vary those 4 parameters, measure drag force, then extract a functional relationship

Dimensional Analysis

- Let's not do it that way (costly, could be difficult, and it turns out that not all of the combinations we could run are independent)
- DA gives us the number and form of independent dimensionless parameters which govern our physical phenomenon
  - How? Buckingham Pi (you have seen this in E72)

Coefficient of Drag

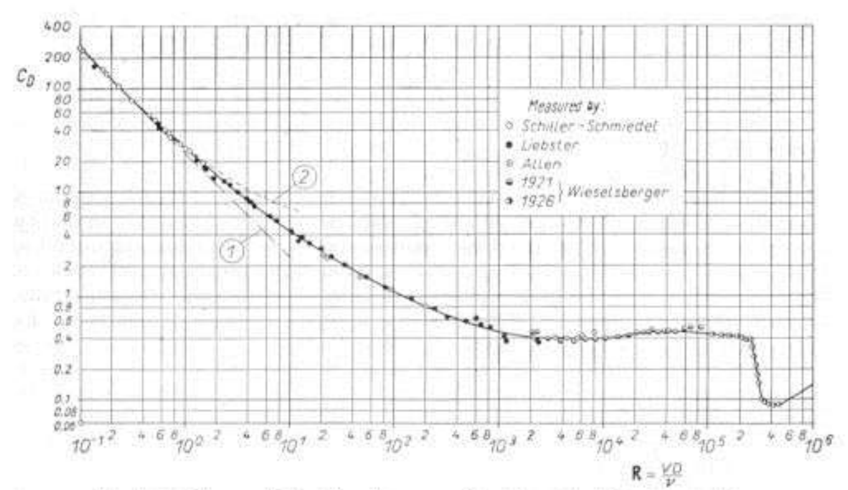
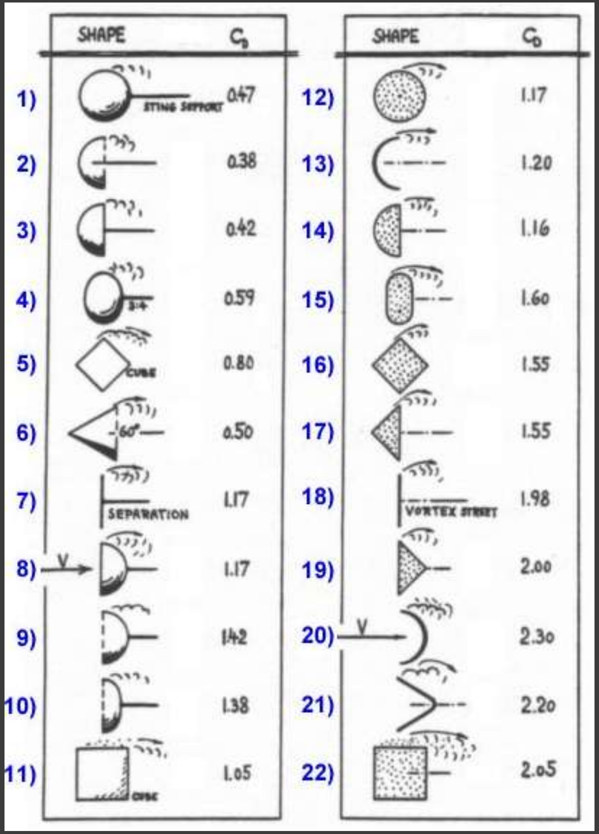


Fig. 1.5. Drag coefficient for spheres as a function of the Reynolds number
Curve (1): Stokes' theory, eqn. (6.10); curve (2): Oseen's theory, eqn. (6.13)



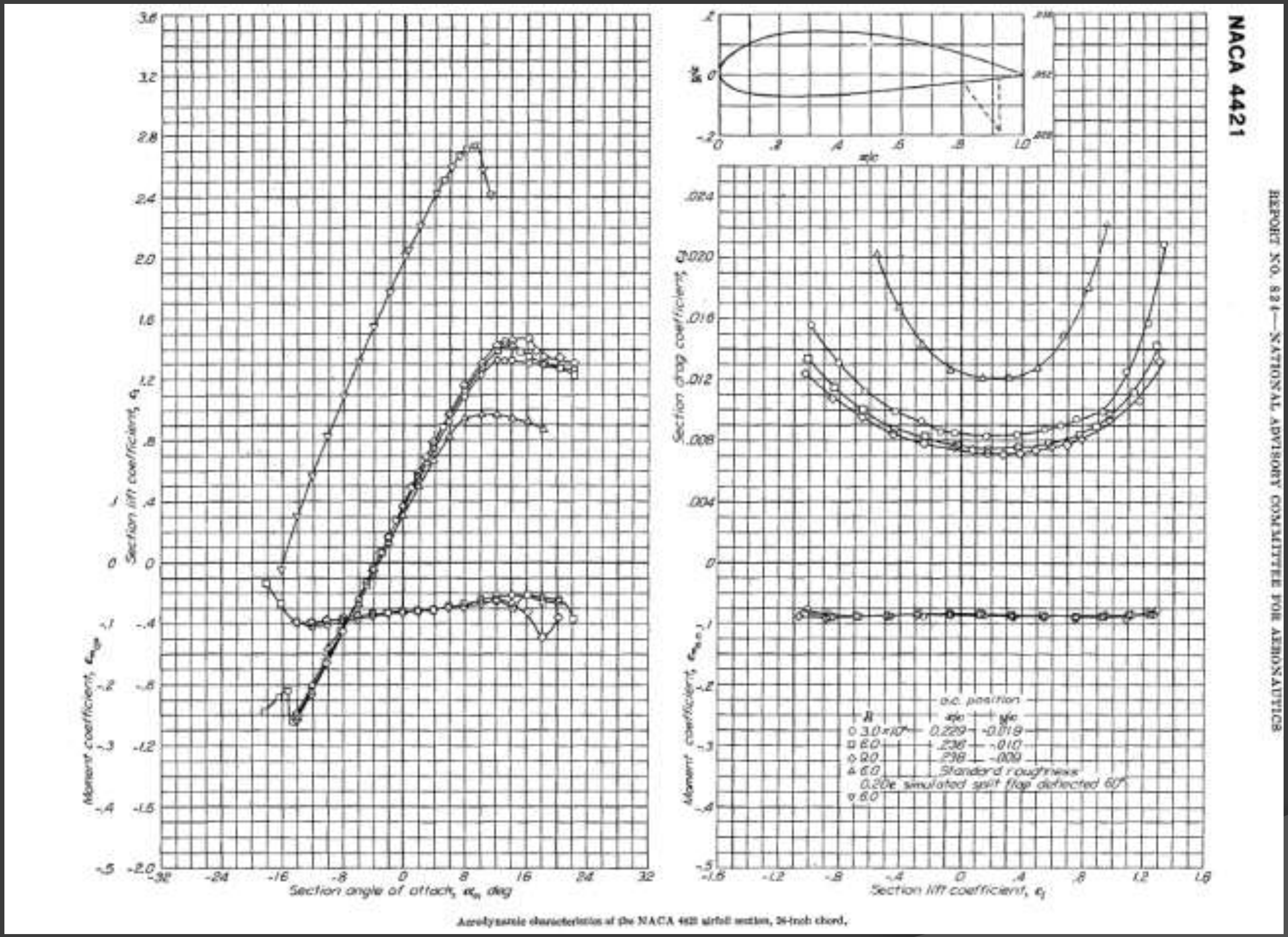
Cd of spheres as f(Re)

100000<Re<1E6

3d on left, 2d on right

http://www.uh.edu/engines/epi1529.htm
http://www.aerospaceweb.org/question/aerodynamics/drag/drag-shapes.jpg

Aero characteristics for NACA 4421 airfoil



Aerodynamic characteristics of the NACA 4421 airfoil section, 24-inch chord.

http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930090976_1993090976.pdf

What area to use in force coeffs?

- Spheres?
- Airfoils?
- Rockets?
- Foreshadowing
  - How does OpenRocket use these?
  - RockSim?

Implications beyond E80

- Lowered drag coefficients for vehicles
  - Aviation efficiency
    - Fuel cost have been driving this (we see big leaps in drag reduction when fuel price increases)
  - Car efficiency
    - Toyota Prius: drag coefficient of 0.25
    - Mercedes G Class: drag coefficient of 0.53

http://ecomodder.com/wiki/index.php/Vehicle_Coefficient_of_Drag_List