Cayley

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

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
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.
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

- \( F_L = \text{lift} = \frac{1}{2} \rho V^2 A C_L \)
  - Where \( \rho = \text{free stream density} \)
  - \( V = \text{free stream velocity} \)
  - \( A = \text{reference area} \)
  - \( C_L = \text{lift coefficient} \)

- \( F_D = \text{drag} = \frac{1}{2} \rho V^2 A C_D \)
  - Where \( C_D = \text{drag coefficient} \)

- 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
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

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?
Figure 4. Static pressure errors due to static port hole placement.
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
  - $\mu =$ fluid viscosity
Dimensional Analysis

- We want to determine drag force on our sphere
- We think that $F_D = f(\text{length-scale, velocity, density, viscosity})$
  - 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

Cd of spheres as f(Re) for 100000<Re<1E6
3d on left, 2d on right

http://www.uh.edu/engines/epi1529.htm
Aero characteristics for NACA 4421 airfoil

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