WIND TUNNEL LAB – Drag and Velocity Measurements

Objectives: 1.) Demonstrate safe start-up and shut-down sequence for the wind tunnel

2.) Set and verify the wind speed in the wind tunnel

3.) Compare drag forces on standard shapes in a flow field to literature values

4.) Model + measure the drag forces on the rocket in various configurations in a flow field

5.) Calibrate the Pitot sensor in the rocket nose cone

* Aerospace engr in general and aerodyn in particular, is an <u>empirically-based discipline</u>. The workhorse for this experimentation is the <u>wind tunnel</u>.

– range from low subsonic to hypersonic speeds

First concept may seem self-evident:

forces on a vehicle are the same whether the vehicle moves @ 100 mph thru stagnant air or whether the vehicle is stationary and 100 mph air rushes over the body ⇒ da Vinci, 16th century

Obviously, wind tunnels keep the body of interest stationary and gas, often air, is impelled at some speed around the body.

History

Francis Wenham @ Greenwich, UK 1871
measured lift, drag.

Horatio Phillips, UK, 1884 airfoil testing
(patented double surface cambered airfoils)

Nikolai Joukowski, Moscow ~~1884~~ 1891
(Zhukovsky) [purchased one of Lilienthal's gliders!]
– wanted to calculate lift mathematically

[others: Mach (Ludwig, not Ernst), Alfred Wells]

1901-1902 Wright Bros. Felt that most of existing aero data were erroneous. Tested 200 airfoil shapes made of wax
⟹ successful airplane

"Our tables of air pressure which we made in our wind tunnel would enable us to calculate in advance the performance of the machine"

So what is a wind tunnel?

- ground-based experimental facility designed to produce flow of gases (often air) to simulate natural flows occurring outside the lab

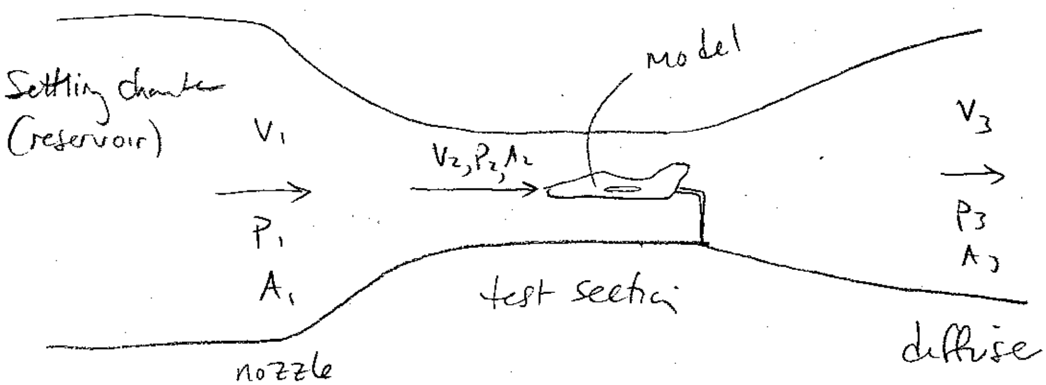
· often used to simulate flows encountered in flights of airplanes, rockets, and space vehicles

range: 27 mph (Wright Flyer) to 25000 mph (Apollo reentry)

↳ many different types of tunnels to cover this range

We'll be using a <u>low-speed subsonic wind tunnel</u>

<u>Simple schematic</u> — side view (cross section)



For low-speed tunnels ($M < 0.3$), $\rho \simeq$ constant

→ incompressible.

Assuming steady quasi-1D flow (uniform vel across cross-section)

<u>cons of mass</u>: $\cancel{\rho_1} A_1 V_1 = \cancel{\rho_2} A_2 V_2$

$\frac{dM}{dt} = \dot{M} = \rho A V =$ constant

$$V_2 = \frac{A_1}{A_2} V_1 \qquad (V_2 > V_1)$$

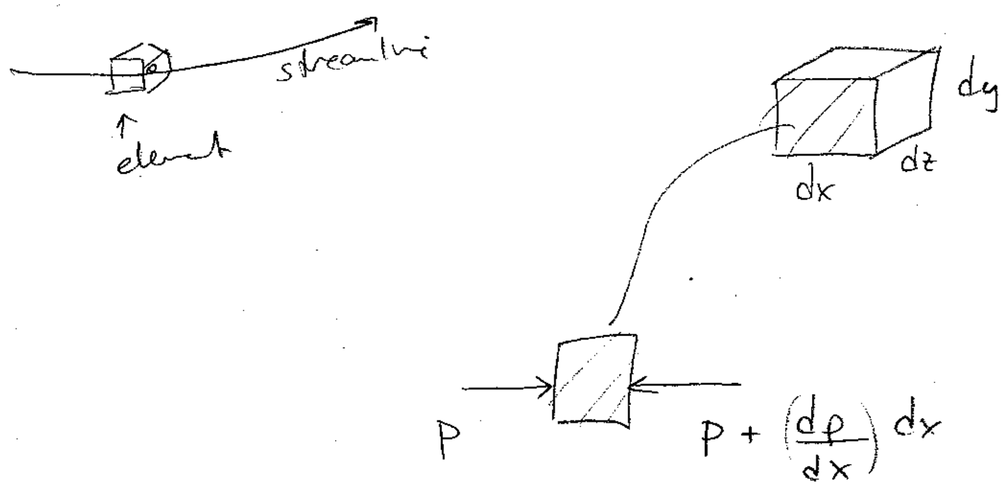
also: $$V_3 = \frac{A_2}{A_3} V_2$$

cons of momentum

→ what about pressure in the flow?
→ relationship between P and V ?

$F = ma$

- infinitesimal fluid element moving along a streamline with velocity V



What acts on this element?

1.) pressure acts in normal direction on all six faces

2.) frictional shear acts tangentially " " " "

3.) gravity acts on mass inside element

For now, let's ignore friction and assume the element is so small that gravity force is negligible.

in x-dir: $\underset{x\text{-dir}}{\sum \vec{F}} = p\,dy\,dz - \left(p + \frac{dp}{dx}dx\right) dy\,dz$

$$\underset{x\text{-dir}}{\sum F} = -\frac{dp}{dx}\,dx\,dy\,dz = m a_x = \rho \underbrace{dx\,dy\,dz}_{d\forall}\, a_x$$

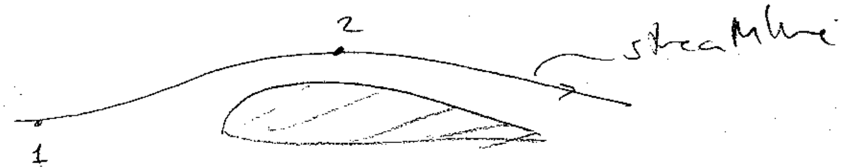
$$a_x = \frac{dV}{dt} = \frac{dV}{dx}\underbrace{\frac{dx}{dt}}_{V} = \frac{dV}{dx}\,V$$

So: $-\frac{dp}{\cancel{dx}}\,\cancel{dx\,dy\,dz} = \rho\,\cancel{dx\,dy}\,dz\,\frac{dV}{\cancel{dx}}\,V$

$$\Rightarrow \boxed{dp = -\rho V\,dV \quad \text{Euler's eqn}}$$

↑ a momentum eqn
neglect friction, gravity
assumed steady flow, incomp

We can integrate this DE along a streamline, say



$$dp + \rho V\,dV = 0 \qquad \rho = \text{const}$$

$$\Rightarrow \quad p_2 - p_1 + \rho\left(\frac{V_2^2}{2} - \frac{V_1^2}{2}\right) = 0$$

or

$$p_2 + \rho\frac{V_2^2}{2} = p_1 + \rho\frac{V_1^2}{2} = \text{const along a streamline}$$

↑ Bernoulli's eqn

• inviscid (frictionless), incomp. flow

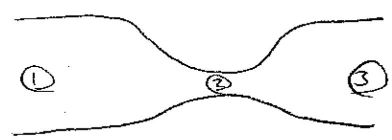
• neglected gravity

• this is $F = ma$, a momentum eqn.

For our wind tunnel, we can use Bernoulli's eqn to get an idea of what happens to pressure w/ velocity

(it's not actually quite correct, as there will be losses in the real world - friction)

However,



$$p_1 + \tfrac{1}{2}\rho V_1^2 = p_2 + \tfrac{1}{2}\rho V_2^2 = p_3 + \tfrac{1}{2}\rho V_3^2$$

practical operation of a wind tunnel is governed by

$p_1 - p_2$ and area ratio of the nozzle, A_2/A_1

$$V_2^2 = 2/\rho\,(p_1 - p_2) + V_1^2$$

w/ $V_1 = A_2/A_1\, V_2$

$$\Rightarrow \boxed{V_2 = \sqrt{\frac{2(p_1 - p_2)}{\rho\left[1 - (A_2/A_1)^2\right]}}}$$

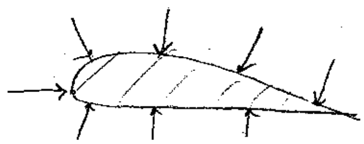
A_2/A_1 fixed once WT is designed, so your "control knob" varies $p_1 - p_2$ to give you desired V_2 (test section velocity)

· LIFT, DRAG

- when we derived Euler's Eqn, we said we were looking @ pressure, friction + gravity forces

- the flow of gas over a body exerts an aerodyn force on the body due to:

1.) distribution of pressure exerted on the surface of the body. P varies from point-to-point; acts perpendicular to the surface.



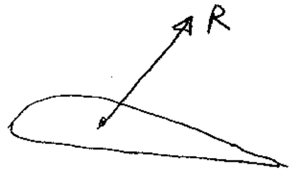
Pressures acting ⊥

2.) shear stress (friction) distribution over the surface. Vary pt-to-pt; act tangentially

shear stress acting tangentially on surface

Integrate:

Resultant aeroforce on body, R; resolved into 2 components



L: lift. Component ⊥ to incoming velocity vector (free stream)

D: drag. Component ∥ to free stream

Two straightforward eqns:

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

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

ρ = free stream density
V = " " velocity
S = reference area (e.g., wing area)
C_L = lift coeff
C_D = drag coeff

} what are these and how do we get them?

Dimensional Analysis and Similarity

- experiments can be expensive
  - best to be efficient in choosing which ones to perform (PLANNING)
- some results can be reduced when suitably nondimensionalized (PRESENTATION, INTERPRETATION)
- Most practical fluid flow problems are too complex to be solved analytically ⇒ experiment, CFD instead
  - result usually presented as data points and smooth curve
  - often more general if expressed in compact form

Dimensional Analysis

- method for reducing the # and complexity of exp. variables that affect a given physical phenom.
  - n dimensional variables will reduce to k dimensionless variables
  - $n - k = 1, 2, 3$ or 4

    generally $n - k$ = # of different dimensions

    (basic dimensions in fluids: mass, length, time, temperature)

Ex: assume the force F on a particular body shape immersed in a stream of fluid depended on body length, L; stream velocity, V; fluid density, ρ; and fluid viscosity, μ.

$$F = f(L, V, \rho, \mu)$$

Experimentally, you might be tempted to vary these 4 parameters, say 10 lengths, and for each length, have 10 V's, 10 ρ's, 10 μ's. $\Rightarrow 10^4 = 10\,000$ exp.

D.A. reduces the # of variables and stops us from running redundant exp.

D.A. $\Rightarrow$ $$\frac{F}{\rho V^2 L^2} = g\left(\frac{\rho V L}{\mu}\right)$$

and both sides are dimensionless #'s

$$\begin{cases} Re \equiv \dfrac{\rho V L}{\mu} = \text{Reynolds' \#} \\ C_F \equiv F/\rho V^2 L^2 = \text{force coefficient} \end{cases}$$

— this just an example, as some flows depend weakly on Re and some depend on other dimensionless #s (Mach, Froude, wall roughness)

NOTE: 2 parameters $\Rightarrow$ $C_F = g(Re)$, g some function

Can get curve by varying Re, say <u>10 values</u>

(contrast to 10^4 values previously)

* Also D.A. can help thinking/planning

- suggests important variables
- can give insight into form of relationship
- can provide <u>scaling laws</u>

cheap, small model to expensive, large prototype

Similarity

- flow conditions for a model test are completely similar if all relevant dimensionless parameters have the same corresponding values for the model and the prototype.

  ↑ complete similarity

<u>geometric similarity</u> – all body dimensions in all 3 coordinates have same linear scale ratio

<u>kinematic similarity</u> – same length scale ratio and same time scale ratio (may require Re or M # equivalence)

[velocity scale ratio will be the same]

<u>dynamic similarity</u> – same length scale, time scale, and force (or mass) scale ratios.

[forces in same ratio and have equiv directions between model + prototype]

↑ pressure, gravity, friction, inertia

for many flows: Re, Fr (Froude #) and possibly Weber # and cavitation #

C_L = lift coeff = dimensionless # = $\frac{\text{Lift force}}{\text{dynamic force}}$

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

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 S} \quad \left[= \frac{\text{drag force}}{\text{dyn. force}} \right]$$

<u>How do we measure forces and velocities in WT?</u>

<u>Pitot-static tube</u> ⇒ <u>velocity measurement</u>

<u>static pressure</u> – what you probably think of when you think "pressure"

– it's the pressure at a point we would feel if we were moving along w/ the flow at that point

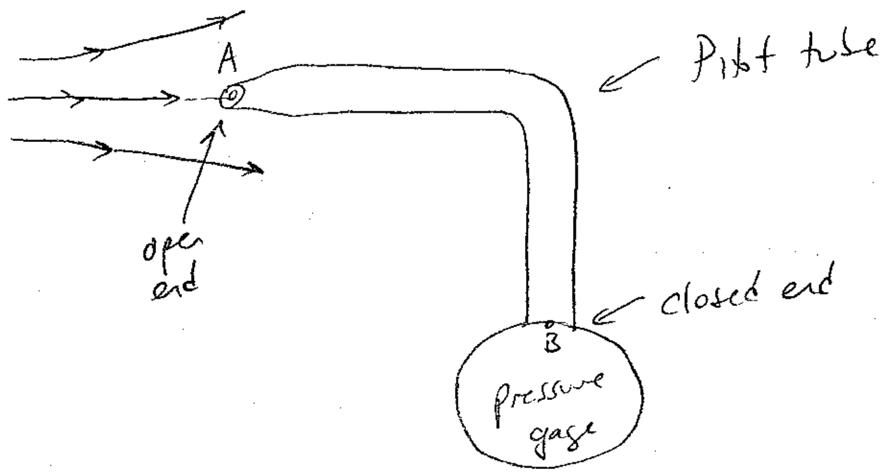
<u>total (stagnation) pressure</u> – imagine a fluid element moving along a streamline. The pressure of the gas in the fluid element is the static P. Imagine grabbing that element and (isentropically) slowing it down to zero velocity. As we do that, P, T, and ρ change (increase)

* Total pressure at a given pt in the flow is the pressure that would exist if the flow were isentropically slowed

down to zero velocity. [imaginary mental process]

P_0 = total pressure.

Pitot tube measures total pressure

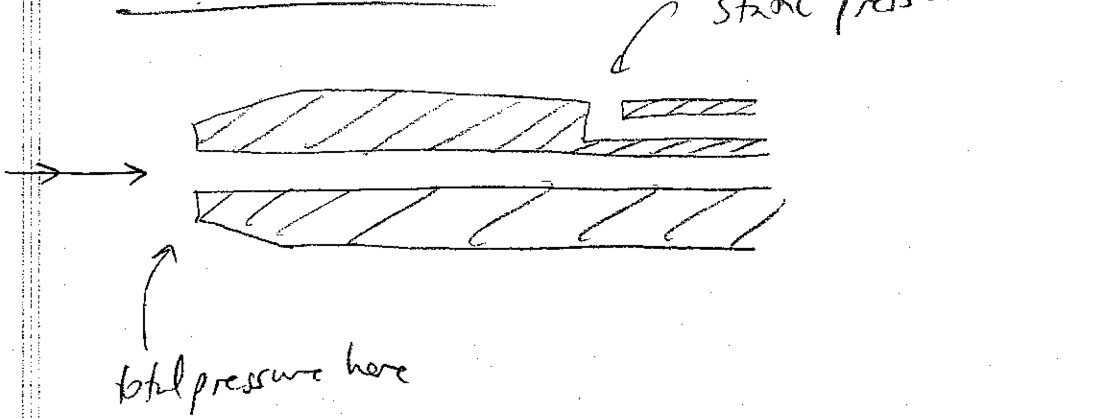


tube is placed parallel to flow

transient process: gas enters tube & piles up; eventually stagnates — no movement — once steady state is reached. pressure @ A is total pressure

(pressure gage @ B measures this)

Pitot-static probe



OK, but we want <u>velocity</u>. How?

recall Bernoulli's eqn:

$$P + \tfrac{1}{2}\rho V^2 = \text{constant} = P_0 + \tfrac{1}{2}\rho \cancel{V_0^2}^{\,0}$$

(incomp flow, inviscid, steady, etc.)

so: $$\boxed{V = \sqrt{\frac{2(P_0 - P)}{\rho}}}$$

tube measures P_0, P

* Usually these differential pressure gages are calibrated in terms of airspeed

<u>Force Measurement</u>

<u>Force Balance</u> - sometime we need to know the force magnitude and its direction

usually are elastic force transducers

- bonded strain gage (define strain gage)
- gross deflection

- balances measure some or all of the forces (and moments) a model experiences
- strain gaged elements relate applied loads to voltage signal
- gross deflection balances often use LVDT (linear variable differential transformers) to relate the

deflection of an elastic element to [illegible]

⇒ moving part in a magnetic field

More on strain gages, more on LVDTs.

<u>Strain gages</u>

If a conductor is stretched or compressed, its resistance changes b/c of changes in length + area and b/c of changes in <u>piezoresistance</u> (dependence of resistivity on mechanical strain)

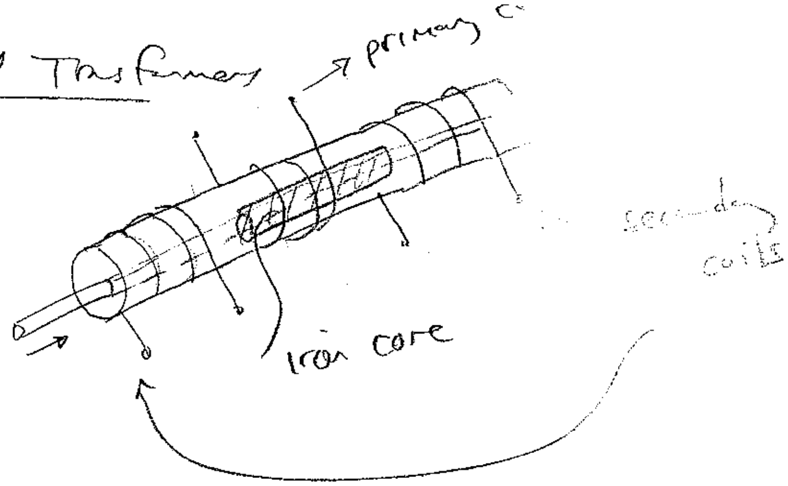
- basically we can relate the change in length to the strain (change in length / length)

- lots of different implementations
  - metal wire gages
  - metal foil gages
  - thin-metal film gages
  - semiconductor gages

Strain gages used, generally, in instrumentation for stress analysis and in construction of force, torque, pressure, flow, and acceleration transducers.

⇒ unbonded metal wire gage ⇒ Wheatstone bridge

Differential Transformers



- sinusoidal voltage excitation in primary coil induces sinusoidal voltage (of same freq as excitation) in the secondaries → but amplitude of that voltage varies with the position of the iron core
- usually set "null" position to be when iron core is in the center; movement from null position causes the differential output to be non-zero (nearly linear function of core position on either side of null). 180 degree phase shift in going through null