ENAE311H – Aerodynamics I

Instructor: Prof. Christoph Brehm

3184 Glenn L. Martin Hall, #3135

cbrehm1@umd.edu

Grader: TBD

Class Schedule: Tues./Thurs., 9:30 – 10:45, ITV 1111

Office Hours: TBD

Textbooks: Fundamentals of Aerodynamics, John D. Anderson (Required)

Introduction to Fluid Mechanics, Fox & McDonald (FM Supplemental)

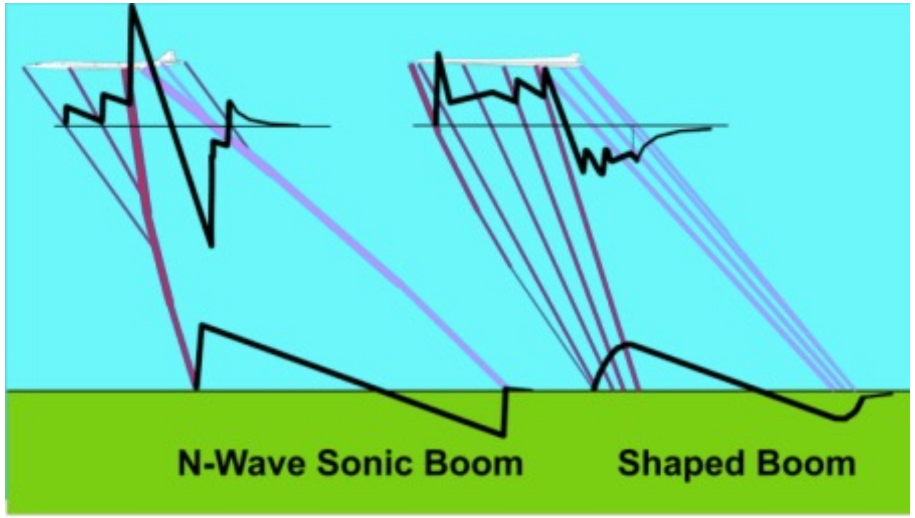
Elements of Gasdynamics, Liepmann & Roshko (LR Supplemental)

Modern Compressible Flow with Historical Perspective, John D. Anderson (A2 Supplemental)

Syllabus and Course Outline: uploaded on Canvas

Class Project:
Low Noise Supersonic Airplane Design Competition

- Design a supersonic airplane (based on Boom Overture)
  - Speed: Mach 1.7
  - Cruising Altitude: 60,000 ft
  - Passengers: 65 (premium-configured 1-1 cabin)
  - Full-scale length: 200ft (CFD analysis at 1:10 scale)
  - Wingspan: 60ft
  - Max takeoff weight: 170,000lb
  - Powerplant: 3 x Rolls-Royce medium-bypass turbofans without afterburners, 17,500 lbf (78kN) thrust
  - **It's expected that this could cut travel time in half, with New York to London flights taking 3hr15min, Tokyo to Seattle flights taking 4hr30min, etc.**
- Split up the design process into several parts
  - 2-D airfoil design
  - 3-D wing design
  - add streamlined main cabin without vertical stabilizer and no engines
- 28 students are split up into 4 teams
  - Split up team into 1 team captain, 2 CAD designers, 2 meshing and 2 CFD specialists
- Deliverables: 1 report describing the design and analysis are due at the last day of classes (limited to 20 pages) and a final presentation (20mins and 10mins Q&A)
- Evaluation Criteria: noise signature, correctness of analysis, how closely are the design parameters met?, as well as cabin comfort. (33% evaluation of presentation by your peers and 66% instructor)



Introduction

ENAE311H Aerodynamics I

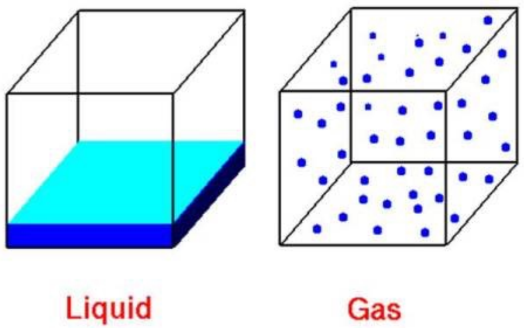
Christoph Brehm

Definitions

- *What is aerodynamics?*
  - A branch of fluid mechanics dealing with the motion of air (or other gases) and its interactions with solid surfaces
  - **External aerodynamics:** forces and moments (also heat transfer at high speeds) acting on bodies moving through air
  - **Internal aerodynamics:** flow of air through ducts, pipes, etc.

- What is a fluid?
  - A fluid is a substance that continuously deforms in response to an applied force (c.f. a solid, which undergoes a finite deformation in response to constant force)

  - **Liquid:** essentially incompressible (constant density) because of strong intermolecular forces
  - **Gas:** compressible because intermolecular forces are very weak



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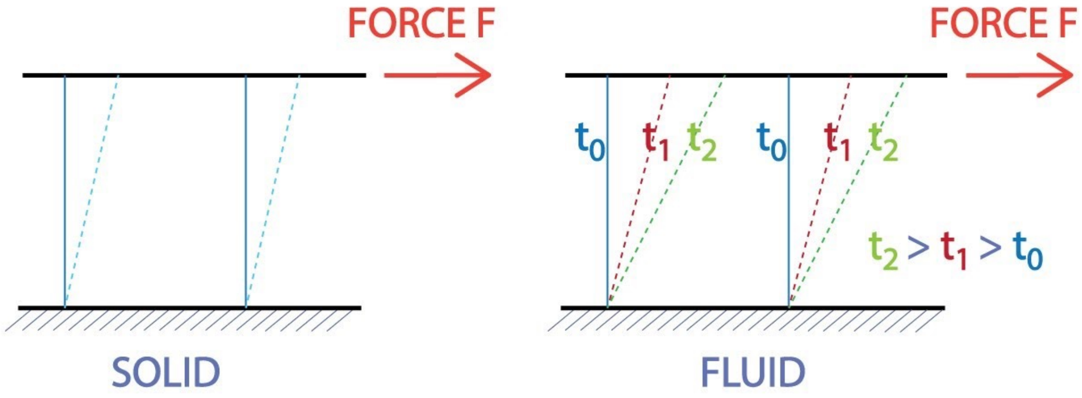

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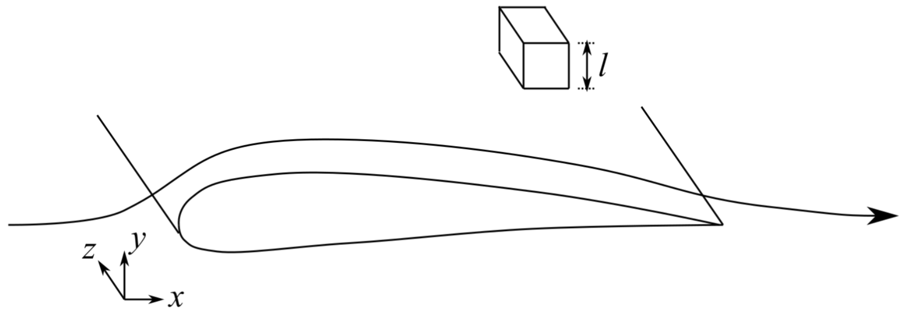
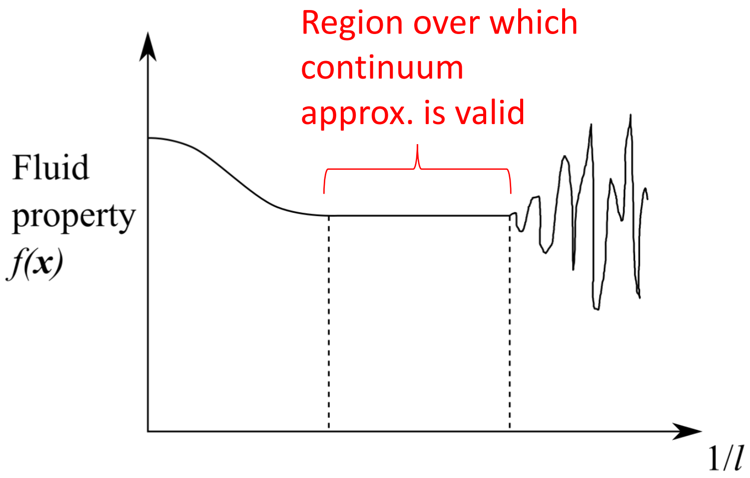
The continuum approximation

- Almost all fluid-dynamical theories treat a gas as a continuum (whereas we know it is composed of discrete molecules)
- Possible because, in macroscopic aerodynamics, typically there will be a huge number of molecules even in a volume corresponding to the smallest length scale of interest
  - For air at STP conditions, there are 2.7×10^{7} particles in box with 1-micron sides
- This means all flow conditions are well-defined and smoothly varying (except, e.g., at shock)





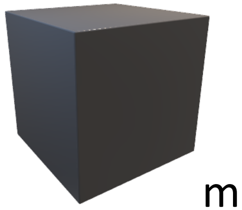
- Note, however, that transport coefficients must be derived from microscopic considerations

Density

- Density is the mass per unit volume of fluid – it is a scalar point property.
- Consider a fluid element at position $\boldsymbol{x}$; the density, $\rho(\boldsymbol{x})$, is defined as

$$\rho(\mathbf{x}) = \lim_{dv \to 0} \frac{dm}{dv}$$

volume = dv



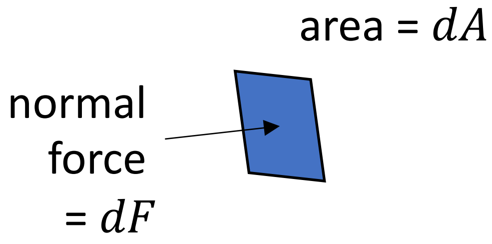
mass = dm

- At low speeds (M<0.3), air can generally be considered a constant density fluid.

Pressure

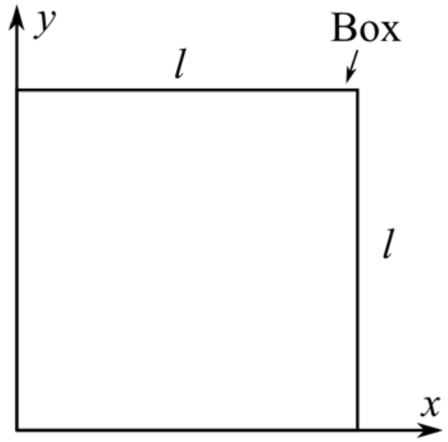
- Pressure is the force per unit area acting on a surface (real or imagined), moving at the bulk velocity of the flow – it is a scalar point property.
- Consider a fluid area element at position $\boldsymbol{x}$ moving with the fluid; the pressure, $p(\boldsymbol{x})$, is defined as

$$p(\mathbf{x}) = \lim_{dA \to 0} \frac{dF}{dA}$$



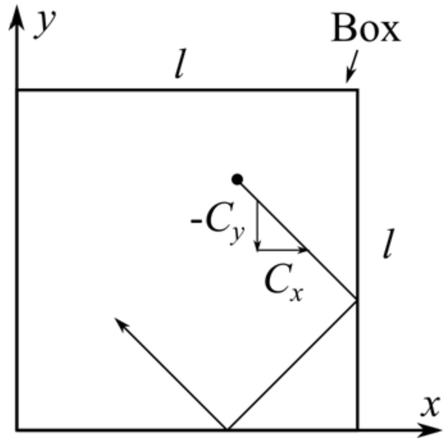
Pressure

- Pressure is related both to the density of the gas and the average random speed of the molecules that make it up. To see this, we consider a particle bouncing around inside a cubical box.



Pressure

- Pressure is related both to the density of the gas and the average random speed of the molecules that make it up. To see this, we consider a particle bouncing around inside a cubical box.
  - For simplicity, consider just a single particle colliding with x-normal wall (assume specular reflection)
  - Momentum transferred per collision: $2m|C_x|$
  - Time between collisions: $2l/|C_x|$
  - ⇒ Momentum deposited per unit time (force): mC_x^2/l
  - ⇒ Pressure from one particle: $mC_x^2/lA = mC_x^2/V$



Pressure

- Pressure is related both to the density of the gas and the average random speed of the molecules that make it up. To see this, we consider a particle bouncing around inside a cubical box.
  - Summing over all particles, we have

$$p(\mathbf{x}) = \frac{1}{V}\sum_i m_i C_{x_i}^2$$

  - Note we can repeat for y- and z-normal walls, sum and divide by 3 to obtain

$$p(\mathbf{x}) = \frac{1}{3V}\sum_i m_i (C_{x_i}^2 + C_{y_i}^2 + C_{z_i}^2) = \frac{1}{3V}\sum_i m_i C_i^2$$

  - From our definition of density

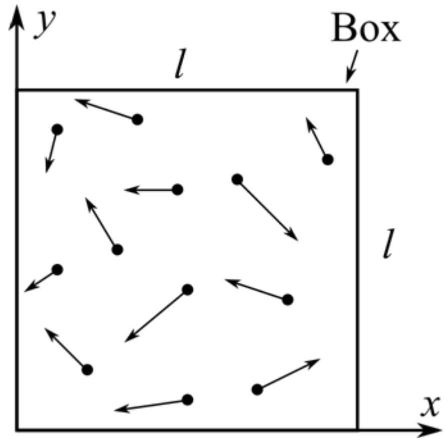
$$\rho(\mathbf{x}) = \frac{1}{V}\sum_i m_i$$

  - And defining the mean-square molecular speed

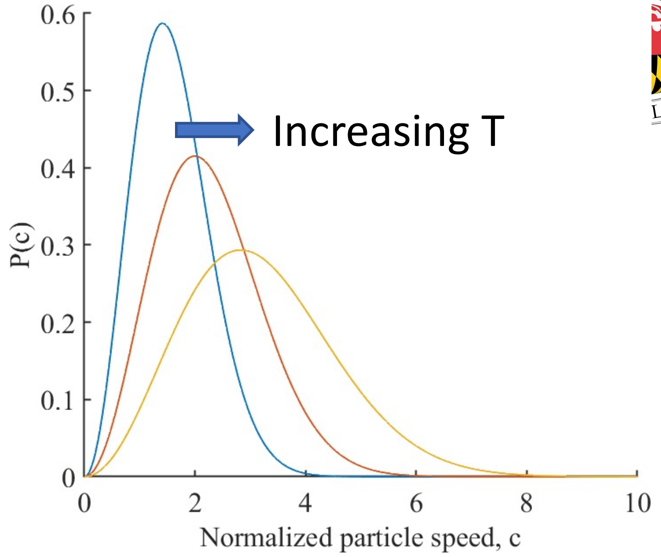
$$\overline{C^2} = \frac{\sum_i m_i C_i^2}{\sum_i m_i}$$

  - We obtain:

$$\boxed{p = \frac{1}{3}\rho\overline{C^2}}$$



Temperature



- Temperature is a thermodynamic property related to the average random kinetic energy of the molecules within the gas. It can be defined as

$$E_{tr} = \frac{3}{2}\mathcal{N}\tilde{R}T$$

where E_{tr} is the total random molecular kinetic energy, $\mathcal{N}$ is the number of moles of gas, and $\tilde{R}$ is the universal gas constant.

- Noting that $E_{tr} = \frac{1}{2}\sum_i m_i C_i^2$ and comparing for our earlier expression for pressure, we can write

$$pV = \mathcal{N}\tilde{R}T \qquad \text{or} \qquad p = \rho RT.$$

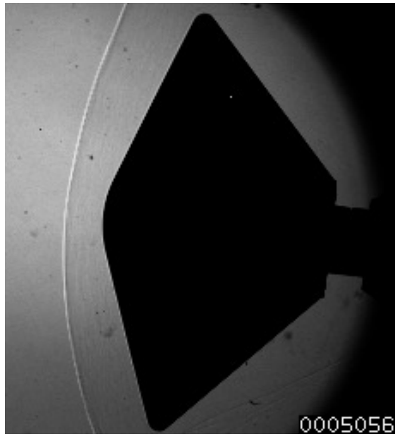
These are alternative expressions of the ideal gas law.

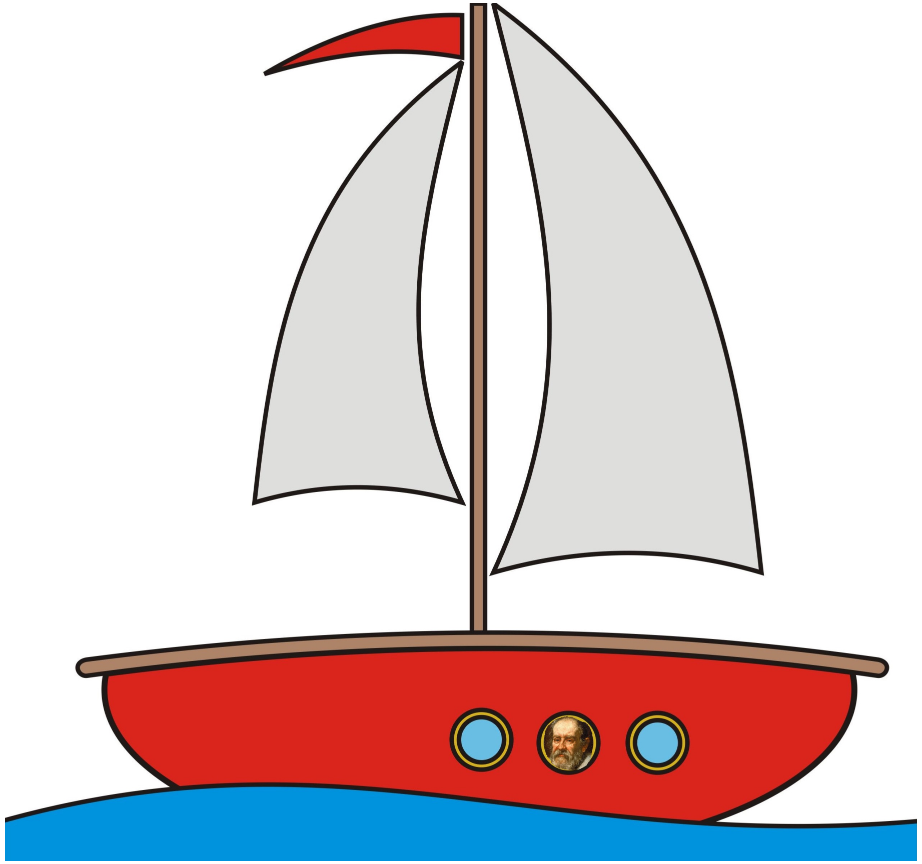
- At low speeds, temperature is essentially a passive scalar quantity (only way it affects the flow is through the viscosity) but for compressible flows it plays a much more important role.

Velocity

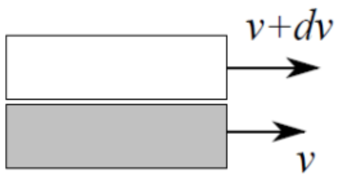
- Fluid velocity, $\boldsymbol{v}(\boldsymbol{x}) = (u, v, w)$ or (v_x, v_y, v_z), is the mean velocity of a fluid element at $\boldsymbol{x}$.
- We denote the velocity magnitude V.

- An important concept in fluid mechanics is Galilean invariance:
  - "The laws of fluid motion are unchanged in any inertial reference frame." (an inertial frame is one moving at a constant velocity)
  - Note that all purely thermodynamic properties (e.g., p, ρ, T, s) are also unchanged by a shift in inertial reference frame
  - Galilean invariance makes possible the testing of flight vehicles in wind tunnels:





Friction/shear stress



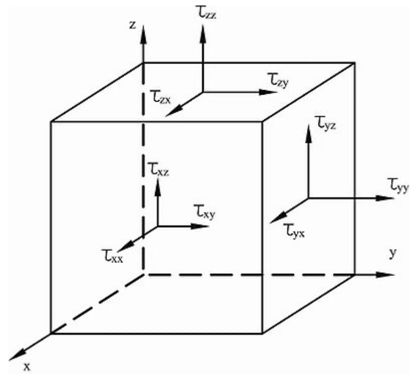
- Consider two adjacent elements of fluid, moving parallel but at slightly different speeds; we can imagine them exerting a tangential "rubbing" force on one another (though the physical origin of this force is the diffusional transport of momentum across their common boundary).
- If this tangential force is dF_f and the area over which it is applied is dA, the local shear stress, τ, is

$$\tau = \lim_{dA \to 0} \frac{dF_f}{dA}$$

- For flow past a solid surface, the shear stress is similarly the tangential force per unit area.
- A *Newtonian* fluid (as are most common fluids) is one for which the shear stress is proportional to the velocity derivative normal to the surface element, e.g., for flow in the *x* direction that changes only in the *y* direction,

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

  where μ, the coefficient of viscosity, depends only on temperature.
- Note that, in general, the velocity has three components, each of which may change in every direction, so the shear stress is actually a 2nd-order tensor (9-element matrix).



Units