A bit of history

Fluid mechanics is a very old field. Over three centuries ago, Sir Isaac Newton devoted an entire book in his work known as *Principia Mathematica* to fluid mechanics (1687). Newton believed that fluid dynamics could be modeled by viewing fluid molecules as rigid particles that obey the classical particle equations of motion. He developed a model for the lift coefficient generated by the airfoils. This model assumed that when the fluid particles hit a solid surface, they lose all their momentum in a direction normal to the surface, and thereafter slide down the sides of the body. This model stated that

\[ C_l = 2\sin^2 \alpha \]

In 1777, D'Alembert (a French scientist) did a series of experiments on ships in canals, and proved that the above equation is wrong. In 1781, Euler (a Swiss Engineer) used theoretical reasoning to show that lift coefficient should be proportional to \( \sin \alpha \), and not to \( \sin^2 \alpha \). Later on we will see that lift behaves like

\[ C_l = 2\pi \sin \alpha \]

From such humble beginnings and false steps, the field of fluid mechanics grew. Many researchers such as Lilienthal (1890s) and Langley (1906) worked on the development of airfoils, gliders and wings. Other researchers and engineers (Rankine 1820-1872, Froude, de Laval, Pelton) worked on turbomachinery, pumps, wind mills and so on, which relied on aerodynamic principles.
"If birds can glide for long periods of time, then ... why can't I?"

*Orville Wright - 1899*

At 10:35 a.m. on a cold, blustery morning, Dec. 17, 1903, Orville Wright carved his place in history by making the first manned, heavier-than-air, powered flight at Kitty Hawk, N.C. The rest is aviation history!

**Aerodynamics is a broad field**

Today, aerodynamics (and fluid mechanics) covers a variety of topics from very low speed incompressible flow (around an insect) to hypersonic flow at Mach 30+ around a reentry vehicle. The flows are viscous, unsteady, compressible, three-dimensional. The fluids may be liquids, air or gas molecules, or ions. As aerospace engineers, you will be called from time to time to solve a variety of internal and external flows. Some of them may be in areas that may appear to have nothing to do with aerospace engineering - e.g. internal cooling of computer systems, flow through ducts and pipes under the hood of an automotive engine, automobile aerodynamics, air-conditioning system design, centrifugal compressors, etc., etc. Our courses and electives (and a life-long commitment on your part to keep up with the technology) will prepare you for all of these, and more.
How are the AE Undergraduate Courses organized?

The aerodynamics courses prepare you for tackling a wide variety of problems. These are organized as follows:

AE 2020 - Deals with incompressible, inviscid and viscous flow. Although the emphasis on external flows over airfoils and wings, the methods are applicable to internal flows.

AE 3450 - Compressibility effects are introduced. A variety of 1-D and quasi-2D compressible flows are solved. Prerequisite: Phys 2122

AE 3021 – High speed aerodynamics and High speed flow viscous effects are introduced. Prerequisite: AE 2020 and AE 3450.

AE 3051 - Teaches the fundamentals of aerodynamic measurements in a hands-on lab setting.

You should try to complete these four courses (with the possible exception of AE 3051) during your sophomore and junior years. These courses are necessary for the Capstone Design course sequence AE 4350-4351 that you will take in your senior year.

These courses are complemented by elective courses on computational fluid dynamics, hypersonics, airfoil design, advanced diagnostics, flow control, and rotary wing aerodynamics. The web site: [www.ae.gatech.edu/undergraduate](http://www.ae.gatech.edu/undergraduate) contains the detailed course outlines of all these courses.

Units - British or Metric?

Most U. S. aerospace and automotive industries use the British system. In this system, mass is given in slugs (equal to 32.2 lbm), distances are given in feet and time is given in seconds. If you are given the mass in lbm units, convert it to slugs, for your own sanity. Likewise, convert distances to feet. The force is given in lb units. One lb of force will accelerate a body that weighs 1 slug at the rate of 1 foot per sec². Work and energy are expressed in ft. lb. (foot-pounds), which may be converted to other units of energy (BTU for example). Power is expressed in ft.lb/sec. And may be converted into other units such as H.P. We will not be dealing with temperature effects in this course. Just for
the record, temperature is given in °F (degrees Fahrenheit) to which we add 463 to convert it to °R (degrees Rankine).

The rest of the world, and even the British, are using or switching to the SI units. Here mass is given in kg, distance in meters, time in seconds, force in Newtons (1 N= 1 kg times 1 m/s), work in Joules (1 J = 1 N times 1 m), and power is measured in Watts (1 W= 1 Joule/s). Temperature is given in °C (degrees Centigrade) to which we add 273 to get °K (degrees Kelvin).

As an aerospace engineer, you should become familiar with both these systems of units.

**Concept of Continuum**

Newton was right in assuming that air is made of molecules, which collide with each other, and obey particle physics. The average distance air molecules (Nitrogen, Oxygen, etc.) can travel before collision with a neighbor molecule is called the mean free path. Normally this mean free path is very small (of the order of $10^{-8}$ m) compared to the dimensions of the wing. Thus, billions of collisions will occur by the time a molecule travels from the leading edge of a wing to the trailing edge. When this many molecules and collisions are involved, it is reasonable to assume that air is a continuous medium, not discrete particles. Properties such as density, pressure and temperature become continuously definable quantities, which are averages of molecule properties taken over millions of molecules. This assumption that the fluid is a continuous medium with continuously varying properties is called the concept of continuum. The concept of continuum fails in the outer edges of rarefied atmosphere where satellites operate, and during the early phases of reentry.

**Compressible Flow vs. Incompressible Flow**

Liquids such as water, by their very nature, are incompressible. It will require enormous forces to squeeze a gallon of water to fit into a volume that is 0.9999 gallons. While computing fluid dynamics of liquids, it is therefore customary to assume that the density of the liquid is constant, and the flow is "incompressible."
Density may be viewed as the mass per unit volume. Let \( \Delta m \) be the mass of the fluid in a small volume \( \Delta V \). Then, density is viewed as the ratio \( \Delta m/\Delta V \) as \( \Delta V \) goes to zero. That is,

\[
\rho = \lim_{\Delta V \to 0} \frac{\Delta m}{\Delta V}
\]

Other fluids such as air are clearly compressible. It is easy to change the density of air inside a small volume by squeezing it with relatively small amounts of force. Thus, flows involving air or gases are usually compressible.

At small velocities compared to the speed of sound, however, the density of the fluid does not change from point to point, even when other properties such as pressure or velocity are changing. Mach number is the ratio of the flow speed to the speed of sound. In AE 3004, you will learn that density of a fluid, starting from rest, varies with local Mach number \( M \) as:

\[
\frac{\rho_{\text{rest}}}{\rho} = \left[ 1 + \frac{\gamma - 1}{2} M^2 \right]^{\frac{1}{\gamma - 1}}
\]

Here \( \gamma \) is the ratio of specific heats (equal to 1.4). The quantity \( \rho_{\text{rest}} \) is the density the fluid will have if it is gradually slowed down and brought to rest. For a Mach number of 0.3, for example, the ratio of densities is only \( \sim 1.05 \), a 5% change. Only at high Mach numbers (e.g. \( M > 0.6 \)) do the changes in density become appreciable.

This course will deal with low Mach number (or low speed) flows. For such flows, it is reasonable to assume the flow to be incompressible.

**Mathematics Background (Section 2.2 in text):**

**Assignment:** Read several times through sections 2.2.1 through 2.2.4

We assume that you know how to take derivatives of a function, perform simple one-dimensional integration, and know basic vector operations such as vector addition, vector subtraction and vector multiplication (dot product and cross product). All the other mathematics will be covered as needed in our course. If you do not understand a mathematical concept, do not hesitate to raise your hand and ask. If I do not know the
answer, I will make up one. Your 23+ friends (who had the same question but were afraid to ask) will be thankful.

**Cartesian Coordinate System:** We will use a variety of coordinate systems. The first is the Cartesian coordinate system. It is represented by three axes, which are perpendicular to each other, as shown below:

![Cartesian Coordinate System Diagram](image)

In this system the position of any point in space is given by \((x, y, z)\), which are distances of this point from the origin, measured along the \(x\)-, \(y\)- and \(z\)- axes respectively.

If we are only interested in two-dimensional problems, then we can drop one of the axes (usually the \(z\)- axis) from consideration.

A fluid particle (which is really a collection of millions of molecules) will have a velocity \(\vec{V}\) in this coordinate system. This velocity is a vector, which has both a magnitude and a direction. It may be viewed as having three components \((u, v, w)\) along the \(x\)-, \(y\)- and \(z\)- directions, respectively. That is,

\[
\vec{V} = u\hat{i} + v\hat{j} + w\hat{k}
\]

The vectors \(\hat{i}\), \(\hat{j}\) and \(\hat{k}\) are called unit vectors (i.e. vectors of magnitude 1) along the \(x\)-, \(y\)- and \(z\)- directions, respectively.

Question: How do you find the magnitude of the velocity vector above?
The properties of a flow are completely defined at a point if we know the velocity vector \( \vec{V} \) (or its three components \( u,v,w \)) and the pressure \( p \). We usually need 4 equations to find these 4 properties. These four equations are:

a) conservation of mass, called continuity
b) conservation of u-momentum
c) conservation of v-momentum
d) conservation of w-momentum

More on these later.

**Cylindrical Coordinate System**: This coordinate system is defined as shown in the following figure:

In this coordinate system, a point in space is defined by its position along the \( z \)-axis, its radial distance \( r \) from the \( z \)-axis, and the angle \( \theta \). Thus its position is given as \((z,r,\theta)\). It may be seen that \( x = r \cos \theta \) and \( y = r \sin \theta \). Thus, knowing \((z,r,\theta)\) means we know the \((x,y,z)\) coordinates as well.

The velocity vector in this coordinate system is given by three components along the radial, tangential and \( z \)-directions respectively. That is,

\[
\vec{V} = V_r \hat{r} + V_\theta \hat{\theta} + V_z \hat{z}
\]
Here $e_r$, $e_\theta$ and $e_z$ are unit vectors along the radial, tangential and z- directions, respectively.

See sections 2.2.2 in the text for discussion of these two coordinate systems. See equation (2.19) and (2.20) for how the velocities are defined in these coordinate systems.

As in the Cartesian case, the flow properties are uniquely defined at any point in space if we know $p$ and the three velocity components $V_r$, $V_\theta$ and $V_z$. We will therefore need four equations (conservation of mass, conservation of momentum in three directions) to solve for these four quantities.

It will be a chore to develop governing equations in each of the coordinate systems separately. Whenever someone comes up with a new coordinate system, we will end up deriving equations specific to that coordinate system. To avoid this need less repetition, we will derive the governing equations once and for all, in a general vector form.