2. Nomenclature and Definitions

In the previous section there are many underlined words that were introduced, without definition. In order to understand what we are discussing, we must make sure that these words, as well as some additional ones, can be defined and that their mention brings a picture or idea to your mind. To this end, we can introduce a picture of an aircraft and its components, and can identify various parts.

The aircraft consists of several main parts, each with an important purpose for maintaining stable, equilibrium flight.

1. Fuselage - The fuselage (or body) generally holds the payload of the vehicle and supports the items below.
2. Wing - The wing of the aircraft is the primary surface used to sustain the aerodynamic lift required to support the vehicle weight.
3. Horizontal tail - The horizontal tail (sometimes called the horizontal stabilizer) is generally a “small wing” at the aft end of the aircraft used to maintain longitudinal (pitch) stability. It also serves to support the elevator control, used to supply the required pitch-moment for equilibrium flight. Some planes may not have a horizontal tail (called tailless aircraft).
4. Vertical tail - The vertical tail (or fin) is one or two “small wings” that project
vertically or near vertically at the aft end of the aircraft. These are use to maintain directional or “weathercock” stability of the vehicle. (There are some recent experimental designs that don’t have a vertical tail, the role of the tail being replaced by engine thrust vectoring). The vertical tail also serves to support the rudder control.

5. **Empennage** - The combination of the horizontal and vertical tail or the entire tail assembly.

6. **Canard** - The canard surface (present on a few aircraft) is a “small wing” at the forward end of the aircraft primarily used to provide pitch control. A canard surface *always* tends to destabilize in pitch. Some aircraft replace the rear horizontal tail with a forward canard (Wright Brothers, Veri-Eze, Voyager), while some aircraft use a canard surface in addition to the horizontal tail (called a three surface aircraft).

In addition to these primary parts of the aircraft, the fuselage and/or wing generally serve to support the propulsion device for the aircraft

7. **Engines** - The engines are used to provide the propulsive force on the vehicle, required to overcome the aerodynamic drag. These devices can be piston-propeller, jet-propeller, or pure jet engines in nature. If a propeller is in front of the aircraft it is called a “tractor” propeller and if aft, a “pusher” propeller.

We can identify additional portions of the above aerodynamic surfaces that can be deflected or moved with respect to the supporting surface that are used for controlling the flow-field about the surface and hence can control to some extent the forces and moments that act on the aircraft. These additional moving surfaces are described below.

**Flaps** - These are moving surfaces at the trailing edge of the wing that deflect downward and aid the wing in providing lift, especially at low speeds. They come in many shapes and sizes and include one, two, or more surfaces that may or not have a gap between them. There are plane flaps, split flaps, slotted flaps, Fowler flaps, and combinations of these. These flaps usually do not cover the whole span of the wing but are partial span devices.

**Leading edge flaps** - These are moving surfaces on the leading edge of the wing that deflect downward. These surface help keep flow attached to the wing at high angles of attack. These can also be plan or slotted. One type of flap that is common is the Krueger flap. The F18/A has a leading edge flap that has its deflection angle scheduled to change with angle of attack.

**Leading edge slots** - These are slots, literally cut just behind the leading edge of the wing so that air can pass from the bottom surface to the top surface of the wing. Such activity helps prevent the wing from stalling. We can combine the flaps and the slots and have leading edge slotted flaps, one variety of which is a Handley Page slot. Sometimes such a combination is called a **leading edge slat**. One of the first aircraft to use extensively leading edge slots and flaps was the Boeing 727. Most current commercial aircraft use these devices.
**Ailerons** - These are similar to trailing edge flaps but are exclusively at the outboard portion of the wing and only span that part of the wing. They are generally “rigged” to deflect in opposite directions at the same time and provide roll control of the aircraft. These are the devices that Glenn Curtiss used to control his early powered aircraft and who the Wright brothers sued as a violation of their patent on wing-warping, the roll control used on the original Wright aircraft.

**Rudder(s)** - These devices are configured like plane trailing edge flaps on the vertical fin(s). They may or may not span the entire vertical fin and they may be “split” into two or more different segments (called a split rudder). This surface controls the yawing moment of the vehicle.

**Elevator** - This device is a trailing edge flap at the trailing edge of the horizontal tail or canard surface. The elevator may or may not span the entire horizontal tail. It can also be split so that the left elevator operates separately from the right elevator. Occasionally the elevator is designed so that it is the same as the horizontal tail. In that case the aircraft is said to have a fully flying tail, and the whole horizontal tail deflects as an elevator.

**Spoiler** - This device is a plate that lies on the upper surface of the wing at around the mid-chord location. It is hinged at its leading edge and can lift up, ruining the nice airfoil shape of that section of the wing and hence “spoil” the flow and reduce the lift. Spoilers are used for roll control, and what is called “direct lift” control, especially in gliders.

## 2.2 Vehicle Axes Systems

In order to better describe vehicle motions and to discuss the forces and moments acting on the vehicle it is convenient to define at least two axes systems, one fixed in the body called appropriately enough, the body-fixed axes system, and one oriented with the relative wind called the wind axes system. These systems are defined as follows:

### Body-Fixed Axes System

The body-fixed axes system is selected so that its origin is at the center-of-mass of the vehicle. The $x^b$ axis points “forward,” the $z^b$ axis points “down” in the vehicle, and the $y^b$ axis completes the right hand set and generally points out the right hand wing. The $x^b - z^b$ plane correspond to a “plane of symmetry” in the vehicle. (There have been at least three planes designed that do not have a symmetry plane, Blohm und Voss BV141, the oblique wing aircraft, and the Scaled Composites “Boomerang”).

The aerodynamic forces and moments in this system are described by the $X_A$, $Y_A$, and $Z_A$ forces along the $x^b$, $y^b$ and $z^b$ body-fixed axes respectively. The aerodynamic moments about these
axes are designated by L, M, and N, and are called the roll, pitch, and yaw moments respectively. Note that L is used both for roll moment and lift. Confusing, you bet! (In the ocean engineering business the roll moment is often designated by a K)

**Wind Axes System**

The wind axes system is selected so that its origin is at the center-of-mass of the vehicle. The \( x^w \) axis is aligned with the relative wind, the \( z^w \) axis lies in the plane of symmetry, and the \( y^w \) axis completes the right and left set. These axes move with respect to the body during a maneuver. The aerodynamic forces along the \( x, y \) and \( z \) wind axes are designated by \(-D, -Q, \) and \(-L\) where \( D \) is called the Drag, \( L \), the lift and \( Q \) the (negative) side force. Sometimes \(-Q = Y^w\) is used for aerodynamic side force. Note that (by definition) drag always acts parallel to the wind and lift acts perpendicular to the wind (and in the plane of symmetry)! The aerodynamic roll, pitch, and yaw moments are designated by the same symbols, \( L, M, \) and \( N \) respectively. A sub or superscript \( w \) can be used to distinguish them from the body moments if necessary.

We can set up a table to summarize these and other conventions:

<table>
<thead>
<tr>
<th>axis</th>
<th>linear disp</th>
<th>angular disp (body wind)</th>
<th>linear rate (body wind)</th>
<th>angular rate</th>
<th>forces (body wind)</th>
<th>moments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x )</td>
<td>( x )</td>
<td>( \phi (\text{roll}) )</td>
<td>( u )</td>
<td>( p )</td>
<td>( X_A )</td>
<td>( -D )</td>
</tr>
<tr>
<td>( y )</td>
<td>( y )</td>
<td>( \theta (\text{pitch}) )</td>
<td>( v )</td>
<td>( q )</td>
<td>( Y_A )</td>
<td>( -Q )</td>
</tr>
<tr>
<td>( z )</td>
<td>( z )</td>
<td>( \psi (\text{yaw}) )</td>
<td>( w )</td>
<td>( r )</td>
<td>( Z_A )</td>
<td>( -L )</td>
</tr>
</tbody>
</table>

* These are “loose” definitions of these quantities

**2.3 Geometry and Definitions Relating to Lifting Surfaces**

The wing, horizontal, vertical tail and canard surfaces are examples of lifting surfaces. The size and shape of these lifting surfaces can be described by certain geometric parameters. For the purposes of discussion, we will consider only wings with straight leading and trailing edges. Such lifting surfaces are called straight tapered surfaces and for a wing, a straight tapered wing.
Of special interest to us are the wing characteristics since this is the primary support (lifting) surface of the aircraft. Of particular importance are the wing span \((b)\), the wing planform area \((S)\), the wing mean aerodynamic chord \((\overline{c})\), and the wing aspect ratio \((AR)\). These same properties (with different values) can be associated with the “small wings,” the horizontal tail and canard and, loosely, the vertical fin.

**Wing span - \(b\) -** the distance from left wing tip to the right wing tip (or vice-versa).

**Wing planform area - \(S\) -** The projected wing area as viewed from above. This area includes the area the wing would have if the fuselage were not present, and the wing span remained the same (same definition for horizontal tail and canard surfaces). Note that the leading and trailing edges are extended to the centerline when calculating the area.

**Wing mean aerodynamic chord - \(\overline{c}\) -** the average chord length from the leading edge to the trailing edge of the wing in an aerodynamic sense (it is not the geometric average). It is defined as:

\[
\overline{c} = \frac{b^2}{S} \int_0^1 c(y)^2 \, dy
\]

This definition has its roots from aerodynamic consideration of the wing pitch-moment and consequently is not the mean geometric chord. For your information, the mean geometric chord is given by:

\[
c_{geom} = \frac{b^2}{b} \int_0^1 c(y) \, dy
\]

**Wing aspect ratio - \(AR\) -** The aspect ratio is a measure of the “slenderness” of the wing and is given by the ratio of the span/mean geometric chord \((b/c_{geom})\). However we seldom use the geometric chord. Instead we can multiply numerator and denominator by the span, \(b\) to get

\[
AR = \frac{b^2}{S}
\]
Associated with each wing, and therefore for each aircraft, are certain important aerodynamic properties. These include the lift-curve slope, the zero-lift angle-of-attack, the stall lift coefficient and the associated stall angle-of-attack, the zero-lift pitch-moment coefficient, and the longitudinal stability parameter or the pitch-moment-curve slope.

2.4 Airfoils

The primary lifting surface of an aircraft is its wing. The wing has a finite length called its wing span. If the wing is sliced with a plane parallel to the x-z plane of the aircraft, the intersection of the wing surfaces with that plane is called an airfoil. This airfoil shape can be different if the slice is taken at different locations on the wing. However, for any given slice, we have a given airfoil. We can now think of the airfoil as an infinitely long wing that has the same cross sectional shape. Such a wing (airfoil) is called a two dimensional (2-D) wing. Therefore, when we refer to an airfoil, you can think of an infinite wing with the same cross sectional shape.

Airfoil Geometry and Nomenclature (2-D)

The figure at the right is a 2-D airfoil section. It consists of the leading edge (LE), the trailing edge (TE) and the line joining the two called the chord (c). The angle-of-attack is generally measured between the velocity (or relative velocity) vector V and the chord line. (Although the angle-of-attack can be defined as the angle between the velocity vector and any fixed line in the airfoil). This angle of attack is defined as the two dimensional angle of attack, \( \alpha_0 \). A line that is midway between the upper surface and lower surface is called the mean camber line. The maximum distance from the chord line to the camber line is designated as the airfoil camber (\( \delta \)), generally expressed as a percent of the chord line, such as 5% camber. The maximum distance between the upper and lower surface is the airfoil thickness, \( t_{\text{max}} \), also designate as a percent of chord length. The we have:

\[
\frac{\delta}{c} \cdot 100 = \% \text{camber} \quad \frac{t_{\text{max}}}{c} \cdot 100 = \% \text{thickness}
\]

As defined earlier, the lift and drag on an airfoil are defined perpendicular and parallel to the relative wind respectively. In addition, we can define the aerodynamic pitch-moment relative to some point on the airfoil (usually located on the chord), with the sign convention that a positive pitch moment is in the direction that would move the nose up. (If we recall, that the y body axis
points out the right hand wing, then the moment about the y axis, using the right hand rule, would give us a nose up moment as positive).

The National Advisory Committee for Aeronautics (NACA) did systematic tests on various shaped airfoils in order to generate a data base for aircraft design. Although performed a long time ago, these data are still used when designing certain appendages of the aircraft. The system consists of a series of 4, 5 and 6 digit airfoils.

**4-digit airfoils (e.g. NACA 2415):**

- 2 - maximum camber is 0.02% over the chord, \( \delta = 0.02 \, c \)
- 4 - the location of the maximum camber along the chord line given as 0.4 \( c \)
- 15 - the maximum thickness, here 0.15 \( c \)

**5-digit airfoils (e.g. NACA 23021):**

- 2 - maximum camber is 0.02% over the chord, \( \delta = 0.02 \, c \)
- 30 - the location of the maximum camber along the chord line \( /2 \), here, 0.15 \( c \)
- 21 - the maximum thickness, here 0.21 \( c \)

**6-digit airfoils (e.g. NACA 63.215):**

- 6 - series designator
- 3 - maximum pressure location, here, 0.3 \( c \)
- 2 - minimum drag at design lift coefficient, \( C_{\text{drag}} \approx 0.2 \)
- 2 - design lift coefficient, here, \( C_{\text{L,design}} = 0.2 \)
- 15 - the maximum thickness, here 0.15 \( c \)

Typically, tail surfaces of an aircraft are symmetric and are made with thin airfoils such as an NACA 0012. (Zero camber, 12% thick).

**2.5 Characteristics of Fluids**

**Fluid Mechanics**

We need to define some properties of fluids (air), that will be important to us a a later time. These include pressure, density, temperature, viscosity, and the speed of sound.

**Pressure:** Pressure in general is defined as a *force per unit area*. Hence the force on any body is the pressure times the area. If we consider a triangular shaped chunk of fluid in static equilibrium, we can sum the forces on it:
Therefore, we see that $P_1 = P_2 = P_3$. That is that the pressure is the same at a given point in a fluid, and that the pressure is a property of the fluid at that point. Pressure is a scalar, and has the dimensions: $[P] = [FL^{-2}]$ with the associated units: lb/ft$^2$ or N/m$^2$.

We can also describe the (scalar) pressure as the following limit:

$$P = \lim_{dA \to 0} \frac{dF}{dA}$$  \hspace{1cm} (1)

**Density**: Density is defined as the mass per unit volume. We can define it as we take a particular volume and keep shrinking it until we get a point of fluid. The density then is

$$\rho = \lim_{dV \to 0} \left( \frac{dm}{dV} \right)$$  \hspace{1cm} (2)

Density is a scalar, and has the dimensions: $[ML^{-3}]$ with the corresponding units: slug/ft$^3$, kg/m$^3$.

**Incompressible flow**: Density is a constant

**Compressible flow**: Density depends on pressure and temperature through the perfect gas law (see below).

**Temperature**: The temperature is a point property that measures the mean molecular kinetic energy. Temperature is a scalar with dimension $[\theta]$ and has the units deg R, deg K. Sometimes we use the Fahrenheit or the centigrade scale, but not when dealing with fluid calculations.

**Perfect Gas Law**: The perfect gas law is a rule that tells us how the pressure and temperature of a perfect gas are related. This law is given by the following relation:

$$P = \rho RT$$  \hspace{1cm} (3)

Here, $P =$ pressure

$\rho =$ density

$R =$ Perfect Gas Constant
The definition of a perfect gas is beyond the level of this discussion. Suffice to say that air behave like a perfect gas.

**Viscosity:** Viscosity of a fluid is the property of the fluid that indicates how the fluid “drags” along the surface that it is flowing parallel to. The force per unit area caused by this fluid motion (not pressure) is called the shear stress. This shear stress is proportional to how rapidly the velocity changes at the surface with displacement away from the surface, the so-called velocity gradient. The constant of proportionality is called the viscosity. We have:

\[ \tau = \mu \frac{dV}{dy} \]

where \( \tau \) = shear stress
\( \mu \) = viscosity

The dimension of the viscosity can be determined from its definition:

\[ [FL^{-2}] = [\mu] \left[ \frac{LT^{-1}}{L} \right] = [\mu][T^{-1}] \]

Then solving for \([\mu]\) (recall that \([F] = [MLT^{-2}]\)):

\[ [\mu] = [ML^{-1}T^{-1}] \]

with the corresponding units: \( \text{slug/ft sec} \), or \( \text{kg/m s} \)

**Speed of Sound:** The speed of sound is just that, the speed at which sound (or pressure waves) would travel through a fluid. It is related to the compressibility properties of the fluid. For example water is barely compressible, and the speed of sound is very fast. Air is more compressible and the speed of sound is slower than water. A measure of how the compressibility of the fluid affects an analysis is by the Mach number, the ratio of the velocity to the speed of sound. Flows at low Mach numbers can be treated as incompressible, while those at high Mach numbers must be treated as compressible. What we mean by high or low is yet to be determined.

The speed of the vehicle through the air (vehicle airspeed) or the speed of the air over the vehicle (also the vehicle airspeed!) can be determined compared to the speed of sound. The result is called the Mach number, \( M_a \), or

\[ M_a = \frac{V}{a} \]

where \( V \) = airspeed
\( a \) = local speed of sound