The Aerodynamics of an Aircraft

PHYS 223: Dr. King

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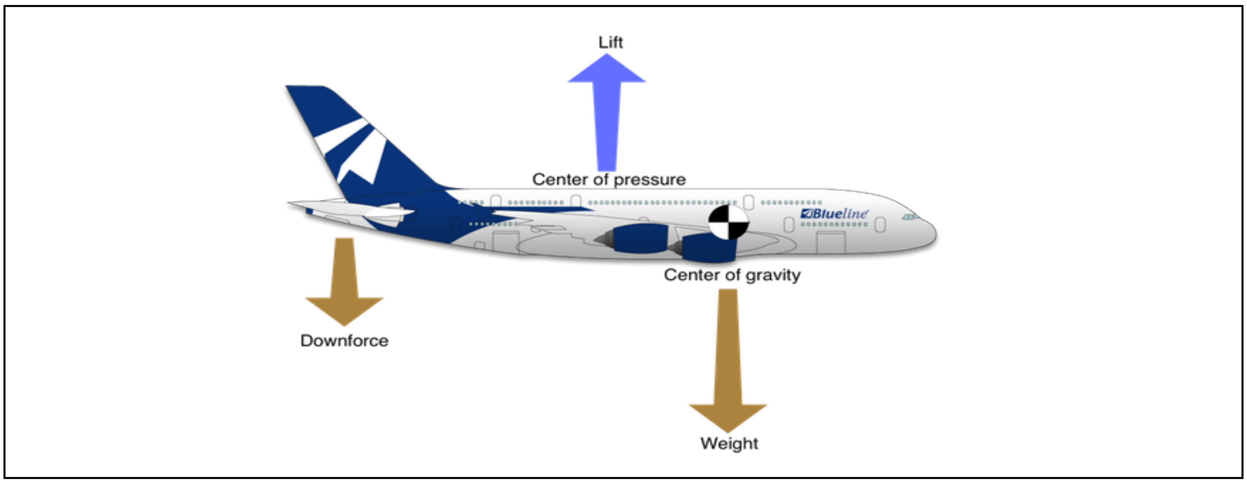
For millennia, humans have been interested in and obsessed with the ability to fly, dating all the way back to ancient Greek times and even 400 BC China. This mixture of gases we call air has been an inseparable part of human life, making the urge to harness it or traverse through it an inevitable reality. However, the first studies of flight did not occur until a little over 500 years ago when a man named Leonardo Da Vinci made plans to build an "ornithopter" which would later be the conceptual basis of modern helicopters. The actual field and study of aerodynamics did not truly develop until the beginning of the twentieth century. At this time the wood and plastic used to build primitive aircrafts was swapped for more durable materials such as aluminum and other various metals. Similarly, the dynamics and engineering contributing to the development of aircrafts was upgraded and advanced by a number of factors including war, industrial advancement, and human drive.

The first image that comes to mind after hearing the word aerodynamics is an airplane, however the field and definition of aerodynamics is actually quite broad. Aerodynamics studies how moving bodies are affected by surrounding fluids and how the relationships between the two can be utilized and enhanced. Airplanes, jets, helicopters, and even racing cars have fundamental roots in aerodynamics which enable them to accomplish feats ranging from flying halfway across the world to driving on an inverted road. The physical components have endured much history and have been refined into the shapes we see today in the sleek design of commercial airliners. These components are engineered to fully utilize the fluid that surrounds them when moving at high velocities. The feat of flight is as intriguing and complex as it is underappreciated. Among today's marvels we can travel from one end of the earth to another in a matter of time as well as breakthrough levels of atmosphere with precision. Many and more accomplishments and feats are based within decades of hard work, analysis, and failure. Just as these feats have undergone much test and error as well as scientific study, the mathematical aspect has pushed aerodynamics experts to found or utilize a number of principles such as the work of Bernoulli. The most basic and essential of which are the four fundamental forces of flight.

There are four forces that act on an aircraft while flying: Weight, lift, drag, and thrust. The ratio of these forces determine whether the plane is cruising, landing, or taking off, as well as how much the plane can carry and how fast it can accelerate. Although a person can define these forces acting on the plane as separate, lift and drag come together to create one integrated force caused by the various pressure force along the plane's body. This net force acts on the center of pressure of the aircraft as seen in the below.



This is the average location of all the pressure applied to the surface of the plane. It is important to know this location to provide stability to the craft or to trim it. To trim an aircraft is to make the rotation around its center of gravity to be zero. Any force acting on the plane a distance from the center of gravity produces torque and therefore rotation. To make sure the rotation is zero, the forces on the plane must be strategically calculated and the center of pressure must be known to produce the perfect conditions of a rotationless aircraft.

The first force, weight, is the most familiar of the four. This force is determined by the level of attraction the plane has to the earth. The weight is calculated by the mass multiplied by the acceleration due to gravity, therefore meaning the more mass the plane has, the greater the weight force. This force works perpendicular to the ground, pulling the plane back down to Earth. An important attribute to the plane which relates to the weight of the plane is it's center of gravity in which the weight of the plane acts through. This is the center of weight of the plane, describing where it rotates about and where it is balanced.

In direct opposition to the weight force is lift. Lift is a mechanical force created by an object moving through a fluid. This force is perpendicular to the flow of direction as well, but points upwards, keeping the plane in the air. Lift occurs when moving gas is disturbed by a solid object. The flow is turned in one direction, and the lift is generated in opposite direction. Lift is mostly generated by the wings of the aircraft as the air flows both over and under them. As eluded to by the name of the force, the plane is "lifted" in order to counteract the weight force pulling it down. When an airplane is cruising at a constant velocity and altitude, the lift and weight force are equal which lets the plane remain at a steady pace and height. When the plane pulls a maneuver such as climbing, descending or banking, the lift vector is tilted with respect to the vertical, making the weight, drag, thrust, and lift to become unbalanced and allowing the plane to pull such maneuvers by having one force act with a greater magnitude than the others in a certain direction. The lift is directly proportional to the surrounding fluid density, the wing area, and the lift coefficient and is proportional to the square of the moving body's velocity as seen in Equation 1. The coefficient of lift, in turn, is calculated using the same equation and when manipulated is shown to be only proportional to the lift force and inversely proportional to the surrounding fluid density, the wing area, and the velocity squared which can be seen in Equation 2.

The way lift is generated has been heavily debated over the years. Some argue that it is the variance of pressure along the planes surface while others prefer to explain it by the velocity of the air around the plane. In actuality, both of these explanations are correct. The father of aerodynamics, Daniel Bernoulli, clarified this with principles he explained within *Hydrodynamica*, one of his most prominent pieces of work. Bernoulli's principles have provided the foundation for both the fields of hydrodynamics and aerodynamics. Bernoulli related the law of conservation of energy to fluids and pressure. This innovation lead to the third equation listed, named Bernoulli's equation, which has a very similar form to the equation for conservation of energy. Bernoulli's equation defining the pressure on the plane and Newton's equations relating the velocity can both be used to calculate the magnitude and direction of the lift force. Since the velocity can differ at different spots of the plane, the pressure must vary too, as Bernoulli states with his equation (*Eq. 3*). Integrating the pressure variation over the plane and multiplying that by the area will determine the force. As for the "Newton" approach, adding up the velocity variation will also give you the lift force value. The integration of the velocities will create a net turning force on the plane and, when Newton's third law is applied, it can be deduced that the turning force will apply an equal and opposite reaction on the plane itself.

This application of lift has allowed moving objects to defeat the issue of weight and enabled those same objects to fly. As mentioned before, this concept is most commonly applied to aircrafts such as a plane. However, this principle can also be applied to moving objects on the ground, namely race cars. Just as the design and shape of a plane can manipulate pressure and speed to lift itself off the ground, race cars or even street cars can use the same dynamics except in the opposite direction, applying a force pushing the vehicle towards the ground so it can hug the road. In theory and actuality, a car could drive upside down on an inverted road using lift to push the car up and cancel out the force of gravity on the car. This idea of lift has many applications and would have many more if not for the third pesky force acting on these moving objects which is drag.

Drag is similar to lift as it is also a mechanical force created by a solid moving through a fluid. In contrast to lift, the drag force works parallel to the direction of travel and in direct opposition to the thrust force. Drag is aerodynamic friction acting in opposition to the direction the plane wants to move. It is caused by the difference in velocity between the plane itself and the air around it. One of the sources of drag is the skin friction between the molecules of the air and the solid surface of the aircraft. Because of this, planes often have a very smooth and glossy finish to eliminate as much skin friction as possible and therefore eliminating drag. The amount of drag can also depend on the viscosity, or "stickiness" of the gas that the plane in travelling through. Another source of drag is induced drag. This is when air flowing off the top of the wings of the plane create vortexes, producing a varying induced flow along the wing. These vortexes the the tip of the wings in turn cause the induced drag and again act as a source of "friction" that the plane's thrust must overcome to accelerate.

Two additional sources of drag are wave drag and ram drag. Wave drag is produced when an aircraft approaches the speed of sound and shock waves are generated that alter the static pressure around the plane, therefore lowering the overall pressure of the system and increasing the drag force. Ram drag is when free stream air is brought into the aircraft. This can happen through the cooling inlets of a jet as well as the engines of a plane. Jet engines intake the stream air, mix the air with fuel, combust the two and exhaust the product to produce thrust. The "negative" thrust from this procedure is known as the ram drag. Just like the lift and weight forces, when the plane is cruising, the drag and thrust forces are equal. The drag force is calculated by multiplying half of the coefficient of friction, the density of the plane, the velocity squared and the reference area (*Eq. 4*).

The thrust force of an aircraft works to push the it forward, generally in the direction that the pilot wants to go. The power of thrust is used when taking off and accelerating in air, overcoming the drag or weight force. As a plane takes off, the thrust force must be greater than the drag pushing the plane back in able to get the jet moving in the right direction and eventually off the ground. When looking at a rocket taking off, we can see that the thrust instead works against weight, as the rocket's goal is to shoot straight up rather than forward like a jet. The objective of the thrust force is to propel the plane forward with enough power to outdo the drag force (or weight force for rockets), allowing the plane to take off and accelerate. However, when a plane is cruising at a steady speed and altitude, the thrust and drag, as stated before, are equal and opposite, cancelling each other out. The thrust force is produced by the engines of the plane. The energy from the thrust force is generated by the combustion of the fuel cells in the engine, which we will go into more depth about later. Other propulsion devices contribute to the thrust force such as the propellers and turbines of the aircraft.

When designing an aircraft it is important to consider the relative positions of the center of pressure, center of mass, and thrust vector. The closer the center of lift is to the center of mass, the more inherently unstable the airplane is. For small personal planes and for commercial airplanes this means that you want the plane designed with distance between the two, increasing stability. If there is too much distance between the two then the plane will tend to pitch nose down, which would result in a crash. Fighter jets are intentionally designed with centers of lift and mass that are very close to one another, which causes the plane to be very maneuverable. Modern fighters use computers to assist in stability to compensate for this. If the center of lift is in front of the center of mass, then the plane will have a tendency to want to flip over until the center of mass is leading, much like the way a dart flies through the air at a dart board.

An aircraft is comprised of thousands of parts, all working together to get the plane off the ground and flying. Whether these are parts of the plane's engine itself, or features to the exterior of the plane that make it more aerodynamic. These components of the plane are fundamental to its flying ability. To begin, we have what constitutes the plane's thrust force: the propulsion system. There are two duties of this system, which are to generate thrust that " must balance the drag of the airplane when the airplane is cruising… and must exceed the drag of the airplane for the airplane to accelerate" ("*Beginner's Guide…*"). This difference between the thrust and drag forces is called the excess thrust. The more excess thrust the plane generates, the faster it is able to fly. A plane that spends most of its flying time cruising does not need to create a great deal of excess thrust and therefore the engineers aim to make the aircraft highly efficient with fuel and energy. To do this, airliners and cargo planes use propellers and fans to accelerate a large amount of gas by a small amount to keep the plane efficiently flying. Burning this fuel turns the propellers and then allows the plane to create a thrust force. For aircrafts such as jets and other experimental high speed aircrafts, a gas turbine engine is used to create the great deal of thrust needed to get to a maximum acceleration. The engine uses the surrounding oxygen to combust the gas. The jet is propelled forward by the high exit velocity of the gas exhaust coming from the rear of the craft, overpowering the drag force and accelerating the plane.

Although the propulsion system of the plane is what generates the power to move the plane through the air, there are many other important parts of the aircraft that work to help or counteract the other aerodynamic forces, giving the plane the ability to maneuver fluently. To begin, we can examine the aspects of the plane that help control lift and drag; The wing, winglet, slats, spoilers, and flaps. The wing of an airplane is in the shape of an airfoil, an aerodynamic, curved shape that easily allows airflow. While most think that the reason lift is generated by the wings is because the air flowing on top is travelling faster so it can meet the air on the bottom but that is false. In reality, the two airflows do not meet at the same time, no matter the difference in distance between them (*Airflow Across a Wing*). The air flowing over the top has a higher velocity and makes it to the back of the wing before the lower air stream does. What this difference in velocity really means is a difference in pressure along different points in the wing. The top of the wing has less pressure pushing on it that the bottom of the wing because of these different velocities and therefore, the pressure force pushing the bottoms of the wings higher overpowers the force pushing the tops down and therefore generates a lift force. This reiterates the former claim that both the pressure and velocity approaches are correct when looking at the generation of lift and further shows to common misconceptions of lift and wings. While the wings produce a lift force, the winglets on the end of the wings help to reduce the induced drag The winglets are the tips of the wings that have the ability to fold up and down. The idea of the winglet is to reduce the vortexes created by the wings tips and make the air flow more two-directional . Winglets have been shown to reduce fuel use by 6.5% which shows their effect on reducing the drag ("*Beginners Guide…*").

Both flaps and slats work to increase lift and decrease drag and are also located on the wings of the plane. These are the folding pieces along the span of the wings with the slats at the front of the wing and the flaps at the trailing end. Both components change the airfoil shape of the wing and add or subtract surface area when taking off and landing. Flipping both of these parts down works by increasing the effective camber of the wing and therefore increasing the lift force. The camber property of the wing is the distance between the chord line (a straight line drawn from tip to tip) and the mean camber line (a curved line following the midway points of the airfoil from tip to tip). A larger camber means more curvature of the airfoil. In contrast to this, when the plane's slats and flaps give the wing a larger surface area, the drag is increased and helps the plane to slow down for landing.

Spoilers are the hinged plates on the tops of the wings of the plane. Just as the flaps and slats, spoilers have the ability to affect lift and drag. The spoilers are used to slow down the plane when in decent. When flipped up perpendicular to the wings, lift is decreased and drag is increased as the spoiler plates add resistance and slow down the craft. By lowering the lift of the plane, this allows the brakes of the plane to work better and let the plane make a smooth landing. As well as slowing down the plane, spoilers can be used to generate a rolling motion when only one is up, making the lift vs. drag ratios of the wings differ.

The rudder, elevator, horizontal and vertical stabilizers, and the aileron are also important aspects on the plane the reduce or produce other types of forces to maneuver the plane. The first four of these parts all reside on the rear of the plane and work to control yaw and pitch. Yaw motion is side to side swaying of the plane parallel to the ground while pitch is up and down motion perpendicular to the ground. The rudder and elevator change the yaw and pitch motions, but the stabilizers control them. The vertical stabilizer is the plate on the rear end of the fuselage point perpendicular to the plane body on which the rudder, a hinged plate, is attached to. While the stabilizer itself provides stability to the plane and keeps it moving straight smoothly, the rudder is able to flap back and forth and control the position of the nose of the plane using the yaw. This rudder has enough yaw control to help a plane land smoothly in strong side-winds, which are winds with velocity near perpendicular to the movement of the plane. However, this rudder does not turn the aircraft, but makes sure the aircraft is aligned in its curve path to perform such a maneuver. To turn a plane, the pilot uses the spoilers and the aileron to bank the aircraft. The horizontal stabilizer and elevator also work together to stabilize the plane by working against the pitching motion and to control the nose of the plane. In contrast to the rudder, the elevator controls whether the nose of the plane is up or down, or in other words, if the plane is ascending or descending. This also means that the elevator is controlling the amount of lift the wings are getting.

There are yet another set of hinged plates on a plane that helps to control the aerodynamic forces and those are the left and right ailerons. These plates move up and down on the wing of the plane to control rolling motion. The two ailerons usually work in opposition to each other: as one is flipped down, the other would be flipped up to make the plane roll to one side. By banking the aircraft like this, the plane can turn in different directions to stay on course. Since the ailerons are located on the back end of the wing, the effective lift on the plane is altered when their positions change the shape of the airfoil wing. If the flap is aimed downward, then there will be more lift in the upward direction and vice versa. Since the lift force acts about the aerodynamic center of the plane, torque is created about the center of gravity and in turn, the plane can rotate and turn.

One thing that must be considered when studying aerodynamics is whether or not the medium you are moving through is compressible or incompressible, as this changes the equations somewhat. For compressible flows, you need to use additional equations, such as the Ideal Gas Law, seen in Equation 5, and conservation of energy. When matter is compressed, its density increases. As a rule of thumb, compressibility only needs to be taken into account when speeds are in excess of mach 0.3, which is roughly 102.9 m/s, although this varies with local temperatures and pressures. When velocities are below that, density changes in gas due to compression are usually below 5%. An important concept when considering compressible flows is the assumption of a “no-slip condition”. This assumption is that the air particles directly adjacent to a moving surface are also moving with the same velocity, leading to a so called boundary layer of air that forms near such a surface.

For compressible flows, different equations or techniques are used depending on the mach number (M) of the flow. The mach number is equal to u divided by c, where u is the speed of the flow or airplane, and c is the local speed of sound for the medium as seen in Equation 6. Figure 1 illustrates the classifications for each type of problem based on different mach numbers. As mentioned before, from 0 to 0.3 the air can be treated as incompressible. From 0.3 to about 0.8 the flow is considered subsonic, meaning below the speed of sound. 0.8 through 1.2 is transonic, which is the transition from subsonic to supersonic. Supersonic is from 1.2 up through about 5.0 at which point it is considered hypersonic flow until a mach number of about 12. After hypersonic flow is hyper velocity flow, which is fast enough that the speed of sound is so small in comparison that it is mostly ignored. An example of an object moving at a hyper velocity is when a spacecraft reenters the earth's atmosphere.

The 0.8 to 1.2 mach, transonic flow is important for fast moving aircraft because within that range some sections of the flow around the craft is supersonic and some is still subsonic. These speeds have massively increased drag in the form of wave drag, mentioned previously. Most aircraft designed to fly at these speeds have a swept wing configuration, because it decreases the wave drag. Another aspect of aircraft designed for these speeds is that they are shaped in such a way as to follow the Whitcomb area rule, also known as the transonic area rule. This rule says that if two cross-sectional areas are the same, then they will also have the same wave drag, even if they have different shapes. This is why some planes have a larger fuselage in the front, that narrows as the wings produce more cross sectional area. As air moves around the aircraft at different speeds, the temperatures vary as well. If any of these temperatures fall to the dew point then clouds can form off of portions of the plane. This leads to a phenomena where a cloud cone follows the trailing edge of the plane nearing supersonic speeds. This can be a problem for rotating propellers as well because velocity in a rotating system is equal to angular velocity times the distance from the point it is rotating around. This means that portions of a propeller going supersonic while other portions of the same propeller are still subsonic, leading to uneven stresses on the material which could lead to failures.

Supersonic flight requires many more aspects of aerodynamics to be addressed. The swept wings mentioned earlier are one such design feature that becomes required when an aircraft is designed for supersonic flight, with the degree of sweep increasing as the maximum velocity is increased. The material that the airplane needs to be built from changes when designing for higher speeds as well because of aerodynamic heating. Aerodynamic heating occurs because of the friction of air particles moving against the various pieces of the aircraft. Many aircraft designed for lower velocities are built primarily out of aluminum, though other alloys are required for high supersonic speeds. This can cause an even greater problem for the jet engines on such an aircraft. Inside a jet engine air is massively compressed which causes more heat. This lead to a necessity to cool the air before it entered the engine, and also designs for quickly moving the heat out of the engine so that it can dissipate more evenly over a greater area. Most jet engines also need their intake air to be subsonic within the engine, so the intakes need to be designed to slow the air down before it reaches the turbines.

When a craft is designed for hypersonic velocities, each one of the problems mentioned for supersonic flight become more and more important. So much so that they can dominate the priority during the design process. A craft designed for hypersonic velocities will have smaller wings, very near the back of the plane, and must be designed out of an alloy that can withstand high temperatures. Because of microfractures caused by thermal expansion, they also may be designed to be used less often, or even for a single use, such as a missile.

For a craft designed to endure hyper velocities the main concern is heat dissipation. These are mainly re-entry craft such as a space shuttle. They use various forms of ablative shielding to bleed off kinetic energy in the form of heat until they reach safer speeds. Many re-entry crafts have their main heat shielding on one side of the craft, meaning that if they are oriented incorrectly when entering the atmosphere, they could burn up before ever reaching safe velocities.

The science and mathematics behind an aircraft are grandiose. The preciseness of all the parts perfectly in place and shaped and the and the anticipation of what the environment at the altitude of flight will be take a great deal of ingenuity and extensive planning. Some of us have never flown on one of these incredible flying machines, while others board one every day, not truly knowing the work and innovative thought that went into producing such a contraption. The study of aerodynamics has allowed us to create and improve upon many forms of transit. With the ability to understand how an object can fly and what forces act on it, engineers have been able to do the impossible such as sending rockets to the moon, carrying almost 1000 passengers across the world at a time, and driving a car upside down, all while defying gravity. To fully understand all the thought, process, and mathematics that goes into the study and manipulation of aerodynamics and its forces is a difficult task. Ideas and and theories are still being researched today. The field of aerodynamics will keep expanding into something even more intensive, brilliant, and what most of the world at one point thought was simply impossible and these advancements all start with the drive and the urge to know how a plane flies.

Works Cited

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Equations

1: Lift Equation

$$L = Cl \times \frac{\rho \times V^2}{2} \times A$$

2: Coefficient of Lift

$$Cl = \frac{2L}{\rho \times V^2 \times A}$$

3: Bernoulli's Equation

$$P_1 + \frac{1}{2}\rho_1 V_1^2 + \rho_1 gh = P_2 + \frac{1}{2}\rho_2 V_2^2 + \rho_2 gh$$

4: Drag Equation

$$D = Cd \times \frac{\rho \times V^2}{2} \times A$$

5: Ideal Gas Law

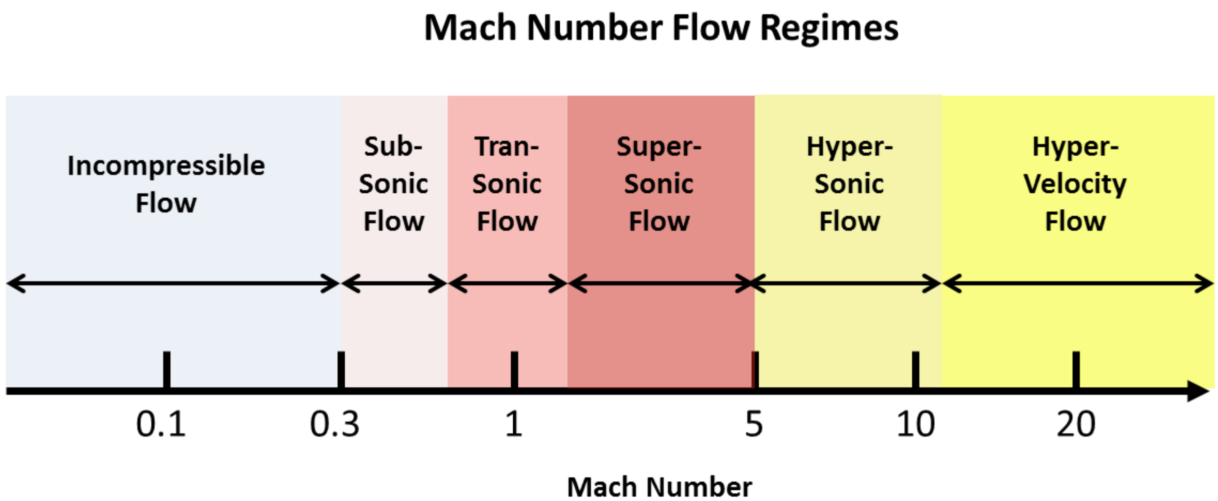
$PV = nRT$

6: Mach Number

$M = u / c$

Figures

Figure 1:



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