LESSON 2

Aerodynamics of Flight

Quick Write

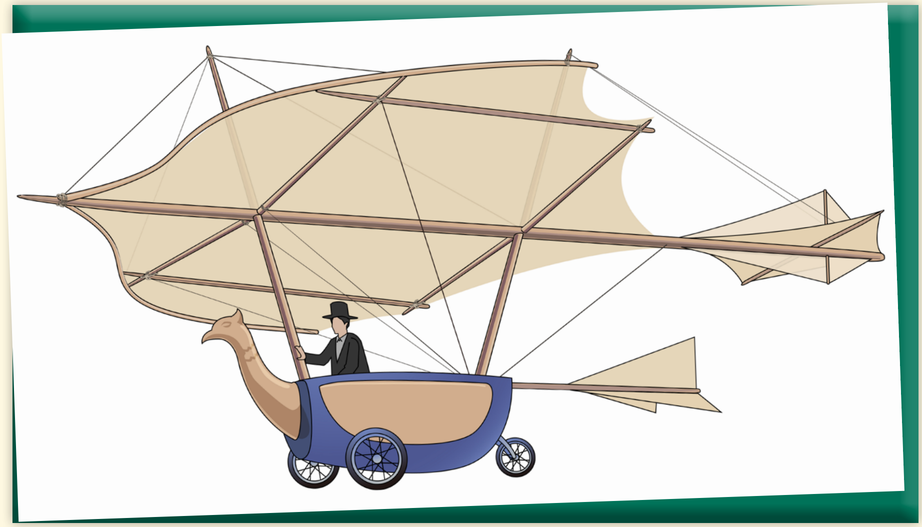
Read the vignette on Sir George Cayley. Do you have a desire to go into the field of aeronautics? What fascinates you about flight? What would you like to learn more about with regard to aeronautics?

Learn About

- four forces of flight
- wingtip vortices
- ground effect

The science of travel through air is aeronautics. Sir George Cayley is credited with being the first person to study and practice aeronautics. He also is considered to be the first person to understand the forces of flight and to establish the modern configuration of an airplane based on those forces. Cayley was born in Yorkshire, England, in 1773. As a child, he was fascinated with flight and began exploring the principles of aerodynamics.

Cayley built his first aircraft in 1796. It was a model helicopter with rotating propellers. Then, in 1804, Cayley designed and built a monoplane glider. In 1810, he published his findings in an article titled "On Aerial Navigation." In it, he identified lift, propulsion, and control as the three elements required for successful flights.



An illustration of Sir George Cayley's glider.
minoru suzuki/Shutterstock

Over the years, he continued to improve his glider and his understanding of the forces of flight. He became the first designer of a glider that successfully carried a human being. His test subjects were a 10-year-old boy who was a passenger in one short flight in 1849 and his coachman (the driver of his horse-drawn carriage), who flew on a large gliding machine in 1853.

Today, Cayley is considered the first aeronautical engineer. While many of his counterparts were still focusing on flight based on bird's wings and different theories of flight, Cayley is credited as the first to focus on fixed-wing aircraft. His discoveries and research laid the foundation for generations of flight enthusiasts.

Vocabulary

- aeronautics
- airspeed
- induced drag
- parasite drag
- fairings
- fillets
- vortex
- condensation trails
- winglets
- turbulence
- wake turbulence
- ground effect
- downwash

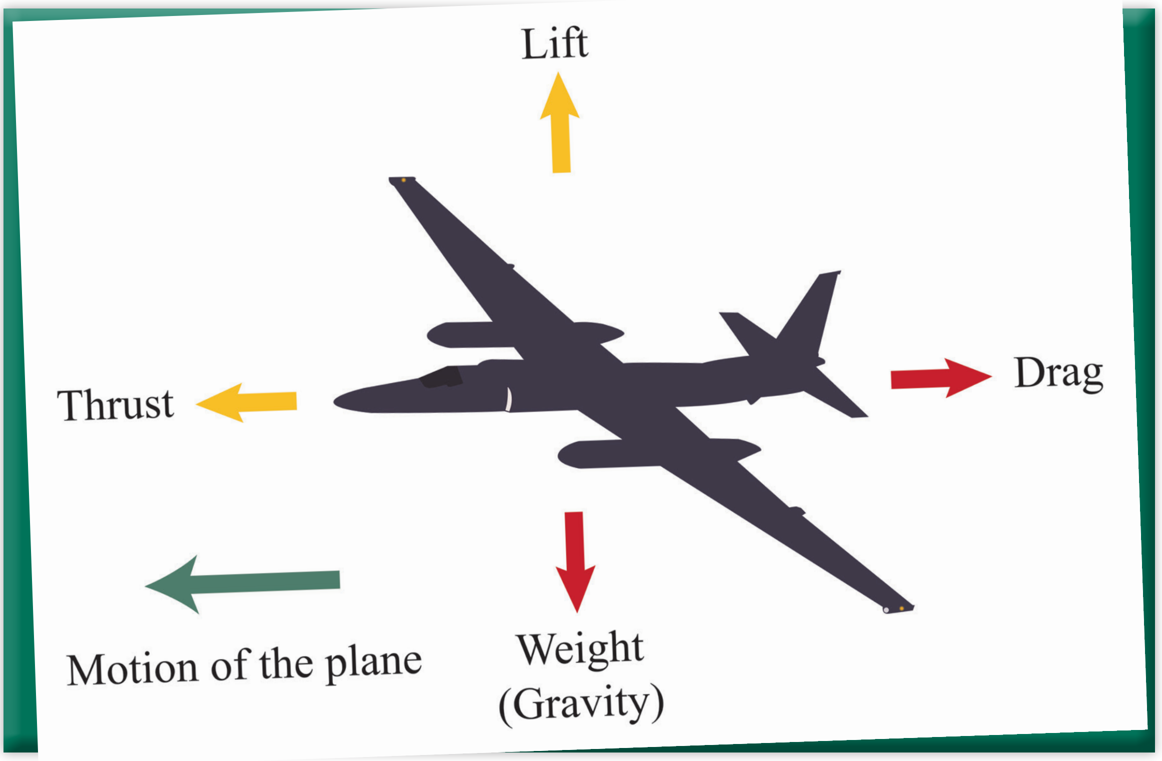
A replica of George Cayley's glider at the Yorkshire Air Museum in the United Kingdom.

Alan Wilson/Wikipedia Commons

Four Forces of Flight

Do you know the science behind flight? We see aircraft zooming through the sky and taking off at airports on a regular basis, but have you ever wondered what allows those aircraft to actually fly? The key to achieving flight involves balancing four forces:

- Lift – The force produced by the reaction of air on the airfoil
- Thrust – The forward force produced by the engine
- Drag – The backward pulling force created by the disruption of airflow
- Weight – The weight of the aircraft, including the crew, fuel, and cargo



The four forces balance each other out in level flight.
Sansanorth/Shutterstock

During level flight, the four forces are balanced and the sum of all of the forces is equal to zero. The forces do not actually equal one another, they just cancel each other out. For example, the weight of the plane is pulled down by gravity, but lift pushes the aircraft up into the air. When these two forces are equal, the aircraft is maintaining level flight.

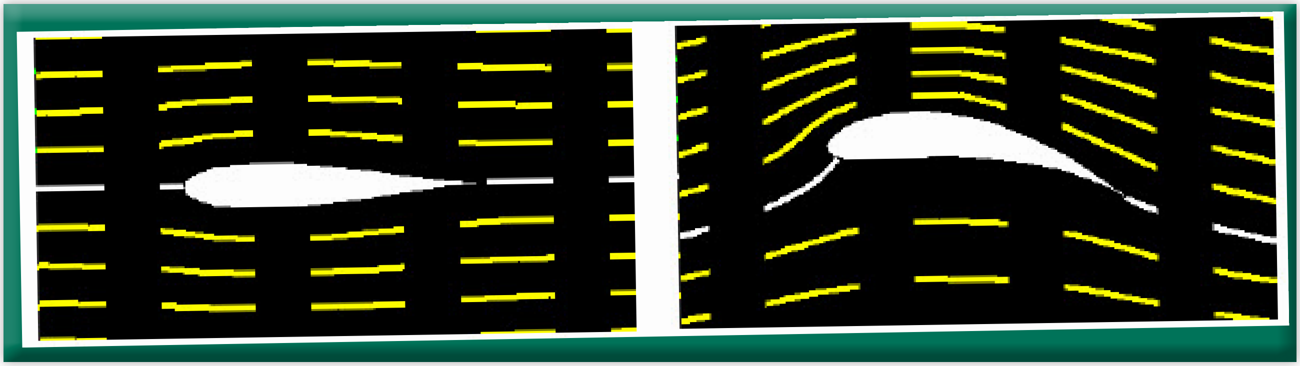
Lift

As previously discussed, lift is the upward force that pushes an aircraft into the air. Lift is created when the pressure above the airfoil is lower than pressure below the airfoil. Lift is a force that can be controlled by the pilot. When the pilot accelerates the aircraft, the plane moves forward and wind flows under and over the wings to create lift.

The airfoil is designed to allow an aircraft to achieve lift. As air reaches the airfoil, the air is forced up over the wing and downward under the wing. Lift is created when the pressure below the wing is greater than the pressure above the wing. The amount of lift generated depends on the amount of air flowing over the airfoil, which in turn depends on the shape of the airfoil.

Remember in the last lesson, we learned about the camber of the airfoil, which is essentially the curviness of the airfoil. The camber changes the shape of the wing, which then changes the flow of air over the wing. As the air molecules approach the tip of the airfoil, they separate with one moving over the top of the wing and one over the bottom of the wing. But the laws of physics help us understand that those air molecules will meet back up at the trailing edge of the airfoil at the same time. To do this, the air molecules over the top of the airfoil must move faster than the air molecules under the airfoil—remember, this is what causes lift.

The airfoil shape has a direct effect on the lift and drag on an aircraft. For example, an aircraft with a thin, narrow airfoil, which has less camber, produces less lift, but it also creates less drag. This is why most fighter jets have thin, narrow wings. They move so fast they don't need the extra lift produced by a curvier camber, and they get the benefit of less drag. Now let's examine a fat, curvy airfoil with greater camber. This type of airfoil will produce more lift, but it also creates more drag.



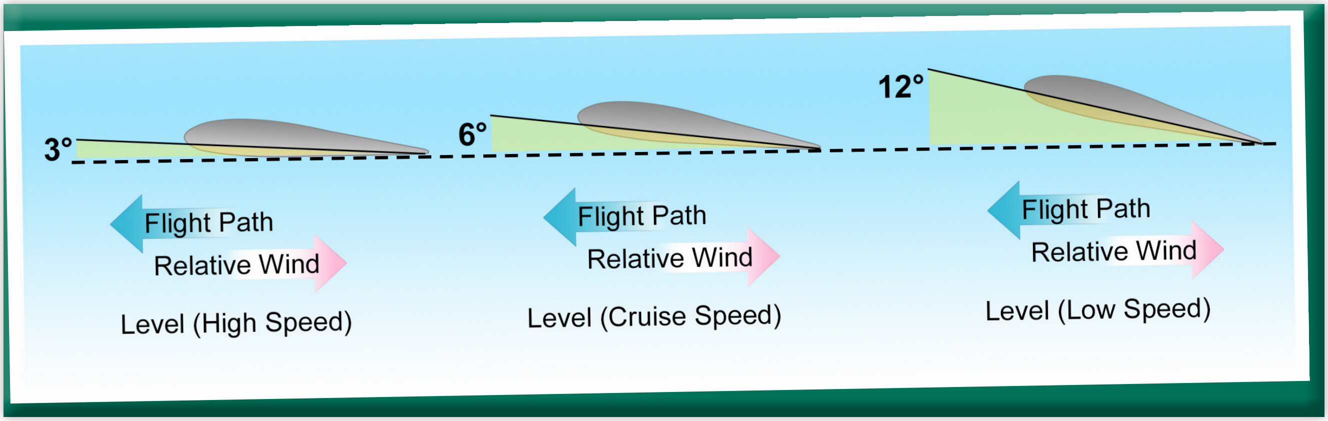
The more the air turns at the trailing edge, the greater the lift.
NASA

Let's look at an example to help understand this phenomenon. Imagine you and a friend represent an air molecule and are simulating lift. We'll use a football field to demonstrate the airfoil. You will run straight across the field simulating the bottom of the airfoil and your friend will run around the track simulating the top of the airfoil. You and your friend start at the same point on the field and need to run to the other side, but you will each take a separate path. The key to the experiment is that you must both arrive at the other side at exactly the same time. To accomplish this task, the person running on the track must run faster than the person running straight across the field. This is exactly what happens when air molecules flow over and under the airfoil. The molecules flowing along the top have to move faster than the molecules on the bottom, creating the difference in pressure and lift. Now let's say the shape of the track changes, this change simulates the change in the camber of the airfoil. Based on the change in the camber or shape, your friend may need to run faster or slower to ensure that you meet at the end of the field at the same time.

The amount of lift an airplane experiences also varies depending on the angle of attack, or AOA, and airspeed, which is *the speed of an aircraft relative to the air through which it is moving*. AOA and airspeed have a direct correlation when it comes to lift. Lift with a large AOA and low airspeed is actually equal to lift with a high airspeed and low AOA.

When flying an aircraft, three general speed regimes are followed: low-speed flight, cruising flight, and high-speed flight. For each of these regimes, the pilot utilizes lift and AOA to control the aircraft.

If the airspeed of an airplane is low, then AOA must be high to maintain the balance of the aircraft. For example, if you are flying an airplane and lower the thrust, then the airspeed decreases as well. The lift will then become less than the weight and the aircraft will begin to descend. What if you don't want to descend, but you want to have a lower airspeed? In that case, you would need to increase AOA to maintain level flight.



At a high speed, a low AOA is maintained for level flight, but at low speeds a high AOA must be maintained for level flight.

AOA adjustments are very important in flight and can be used to maintain the balance between lift and weight. It's important to note that airspeed will naturally adjust to maintain the equilibrium between drag and thrust. Let's look at an example:

> If thrust is increased and AOA is constant, then speed and lift will increase and the aircraft will climb until lift equals weight. In order to maintain level flight, AOA must be reduced.

Any change in AOA needs to be matched with a change in thrust and airspeed. As the example above illustrates, to maintain steady flight, the AOA must be decreased when the thrust and airspeed are increased. Keep in mind that if the AOA is decreased too slowly, the aircraft will climb. If the AOA is decreased too much, the aircraft will descend.

You must also remember the concept of critical angle of attack from the previous lesson. At the critical angle of attack, lift is sharply reduced and the aircraft stalls. The critical angle of attack is typically between 15 to 20 degrees for most airfoils.

Thrust

Thrust is the forward motion of the aircraft and is produced by the engine or propeller (or rotor blades in the case of a helicopter). Thrust works directly against drag, which pulls the aircraft backward. For the aircraft to move forward, thrust must be greater than drag. The aircraft will continue its forward movement and gain speed until thrust is equal to drag. When thrust is equal to drag, the aircraft maintains a constant speed during the flight.

Drag

Drag is the force that resists movement of the airplane. There are two basic types of drag: induced drag and parasite drag.

Induced drag is *the drag created when lift is produced*. It can be seen as a side effect of lift. It's safe to say that nothing is 100 percent efficient, and airplanes are no different. Aircraft designed with a higher efficiency will experience less induced drag. As the next lesson explains, the design of the wings can create efficiencies in flight and help reduce induced drag.

Parasite drag is *the drag that is not associated with the production of lift*. One way to recall the definition of parasite drag is to remember that it incorporates all the forces working to slow the movement of the aircraft. Parasite drag can be categorized into three types:

- Form drag – This is generated by the flow of air over the shape of the aircraft. For example, as air flows over antennas, the air separates then comes back together. This type of drag can be easy to avoid through aircraft design. The more streamlined the design, the less form drag that is created.
- Interference drag – This is created by air that flows around two components of the aircraft, such as the air flowing over the wing intersecting with the air flowing over the fuselage. Aircraft engineers combat interference drag by designing rounded fairings or fillets. Are you wondering what fairings and fillets are? Picture a small aircraft with fixed landing gear, meaning the wheels do not lift up into the aircraft after takeoff. The wheels of this type of aircraft have rounded metal around them—these are fairings, *rounded metal plates that are designed to reduce drag*. Fillets have a similar purpose: they are *rounded pieces of metal placed at intersections on the aircraft to help reduce drag.* Fillets are typically found at the intersection of the wing and fuselage. Engineers also solve the problem of interference drag by designing airplanes with retractable landing gear, which produces much less drag. But there is a tradeoff: retractable landing gear requires a more expensive airplane design.

Fairings can help reduce drag around the wheels of an aircraft with fixed landing gear.
Madison Weller/Shutterstock

- Skin friction drag – This type of drag is created from the contact of moving air against the surface of the aircraft. To combat skin friction drag, designers use flush mount rivets and place a smooth, glossy finish on the outside of the airplane.

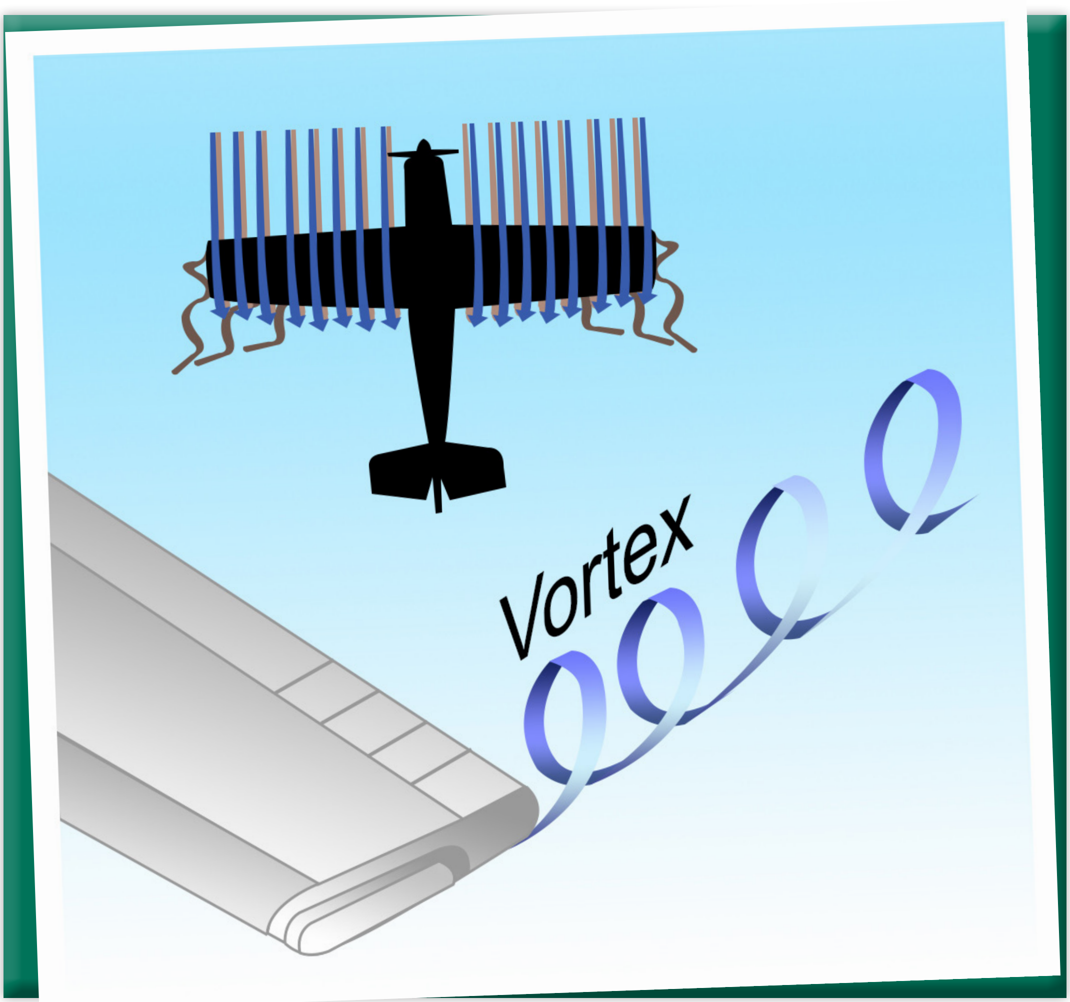
Weight

Weight is the force of gravity exerted upon an object. The force of lift counteracts weight. When lift is greater than the weight of the aircraft, flight will be achieved and the vertical speed will increase. If lift is equal to weight, then the airplane will maintain a constant altitude.

When discussing weight, it's important to take into account all factors that contribute to the total weight of the aircraft. These include the weight of the aircraft, crew, cargo, and fuel on board. Have you ever flown on a small aircraft? The pilot may ask you (or guess) your weight so that they can calculate the total weight of the aircraft prior to takeoff. As we progress through this textbook, we will talk more about how pilots adjust for the weight of the aircraft. In the meantime, we will dive into several concepts that affect the forces of flight. These concepts will help to improve your understanding of how the forces of flight impact an aircraft during flight.

Wingtip Vortices

As we've learned, air moves directionally from high pressure to low pressure. We know that the pressure is higher below the wing in flight. Air will flow using the path of least resistance, which means the air flows toward the tips of the airfoil. The flow of air over the airfoil creates *a whirlpool of air* called a vortex. This is referred to as "wingtip vortex."



A wingtip vortex consists of circulating air off the tip of the wing.

Did You Know?

The wingtip vortices of air circulate in a counterclockwise direction from the right tip and a clockwise direction from the left tip.

A wingtip vortex off the back of the aircraft's wing is like a mini tornado. It is usually invisible. However, during a humid day, water condenses (turns into a visible gas) in the core of the vortex, producing the two streaks of white that can be seen behind the aircraft. But don't confuse this with condensation trails. Condensation trails (contrails) are *the water vapors in engine exhaust that you see streaked across the sky after an aircraft passes overhead*.

Wingtip vortices on display during takeoff.
hlopex/Shutterstock

Vortex Strength

A wingtip vortex is directly proportional to an aircraft's weight and AOA. That is, as weight increases, more lift is needed and the wingtip vortex is stronger. Likewise, as AOA is increased, the strength of the wingtip vortex increases. Vortices can be very dangerous to smaller aircraft. To avoid vortices, pilots should be aware of heavier aircraft flying in the same area so that they can avoid the other aircraft's vortices, which cause wake turbulence.

As the speed of an aircraft increases, the vortex strength surprisingly decreases. This is because flying at faster speeds typically requires a lower AOA. This is why it is critical to be aware of vortices during takeoff and landing.

Heavier aircraft need more lift to achieve flight. The more lift that is needed, the greater the vortex strength. In addition, heavier aircraft typically fly at lower speeds and require an increased AOA, which we know also affects the strength of the vortex. We know that an increased AOA leads to stronger wingtip vortices, which is why heavy, slow aircraft can generate some of the most violent vortices.

The vortices themselves create induced drag on the aircraft. As the AOA increases, there is a greater difference in the pressure between the top and bottom of the airfoils, (which means more lift). This difference in pressure causes more violent vortices, which in turn creates more induced drag and turbulence. Some modern aircraft are now equipped with winglets, which are *the upward facing tips at the end of the wings*. The winglets help reduce vortex formation off the back of the wings. In addition, they also increase lift and improve the fuel efficiency of the aircraft.

Another factor that affects the strength of the vortices is the proximity to the ground. The closer the aircraft is to the ground, the smaller the vortices. This happens because as a vortex of air hits the ground, the ground dissipates the air and stops the vortex from gaining strength.

Winglets

Most wings experience induced drag, which if you recall, is the drag created by lift. The flow of air over the tips of the wings is strongly influenced by induced drag because this is the point where the wingtip vortex is created.

Designers found that induced drag is minimalized with an elliptical wing formation. The long, thin wings produce less induced drag. But elliptical wings are not easy to manufacture so designers came up with a new idea to combat the issue of induced drag—winglets.

Winglets have a nearly vertical (bent upward) airfoil at an airplane's wingtip. The winglet reduces the strength of the wingtip vortex, thus decreasing induced drag. According to NASA's Dryden Flight Research Center, another benefit of winglets is slower fuel burn. Tests have shown a 6.5 percent reduction in fuel use with aircraft around the size of the Boeing 707 when winglets are used.

The winglet is used to reduce induced drag and wingtip vortices.
Podkovyrov Oleg/Shutterstock

Wake Turbulence

If you've ever been on a flight, you may have experienced turbulence or even something called wake turbulence. Turbulence is *a sudden change in airflow by eddies (whirling motion of air) and currents*. In Chapter 3, we'll review turbulence and how to avoid it in flight.

Wake turbulence is t*he disturbance of air that forms behind an aircraft as it passes through the air*. Large aircraft can leave strong vortices behind them, which causes wake turbulence. This is a safety issue for many aircraft. If a light aircraft follows a heavy aircraft, the wake turbulence can cause it to roll, especially during takeoff and landing. Because of this, pilots make adjustments while flying and taking off to avoid wake turbulence. They also can choose to keep their distance from larger aircraft in flight to ensure they are not within the wake turbulence . It is important to consider the ground (or a flat surface) in any discussion of flight, so that will be our next topic.

A smaller aircraft can get caught in the wake turbulence created by a larger aircraft, which would cause it to roll.

Ground Effect

As an aircraft gets closer to the ground, the aerodynamics change. As pilots are landing, they suddenly experience a feeling that the aircraft cannot go any lower. This concept is called ground effect, which is *the aerodynamic phenomenon that happens right before touchdown when it feels like a plane cannot go any lower*. It is caused by the air that gets trapped between the wing and the ground. Have you ever flown on a flight and right before touchdown you feel like the aircraft is floating? This is ground effect. Think of it as an air cushion that a plane is landing onto.

Ground effect occurs because as the aircraft approaches the ground, the flow of air changes. The airflow becomes restricted because of the surface below. This change occurs whether the aircraft is above land or water.

During flight, the wingtip vortices are large, which causes t*he air and vortices to roll off the back of the wing at a downward angle,* which is known as downwash. As the aircraft approaches the ground, the downwash bounces off of the ground surface, reducing drag. As a result, the aircraft experiences an increase in lift.

During landing, ground effect doesn't come into play until the aircraft is within one-half wingspan of the ground. As you experience the increase in lift and decrease in drag, it feels like the aircraft is hovering above the surface. During takeoff, you begin flight with ground effect. This requires an increase in airspeed in order to climb out of ground effect. Figure 1.1 demonstrates ground effect and its influence on takeoff, and Figure 1.2 demonstrates ground effect during landing.

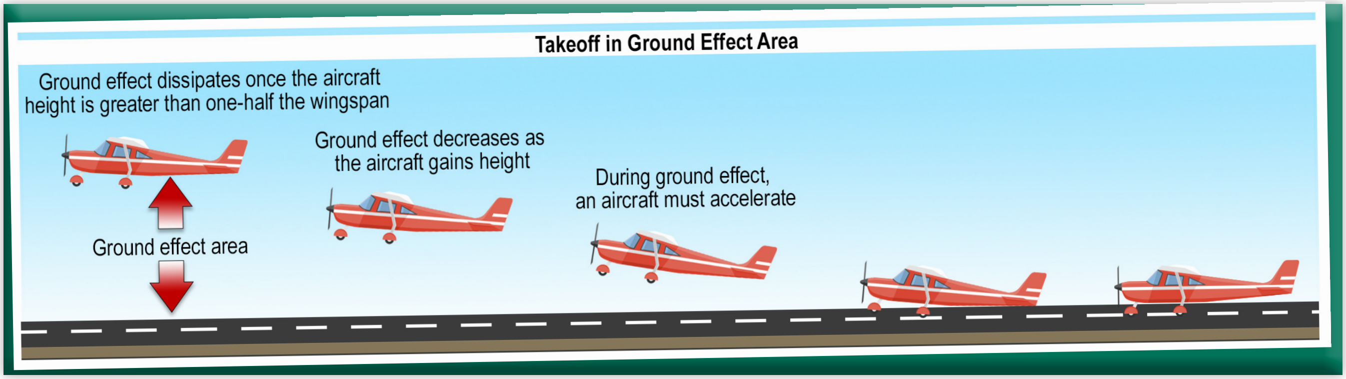


Figure 1.1: During takeoff, aircraft will experience ground effect and need to accelerate to get out of ground effect.

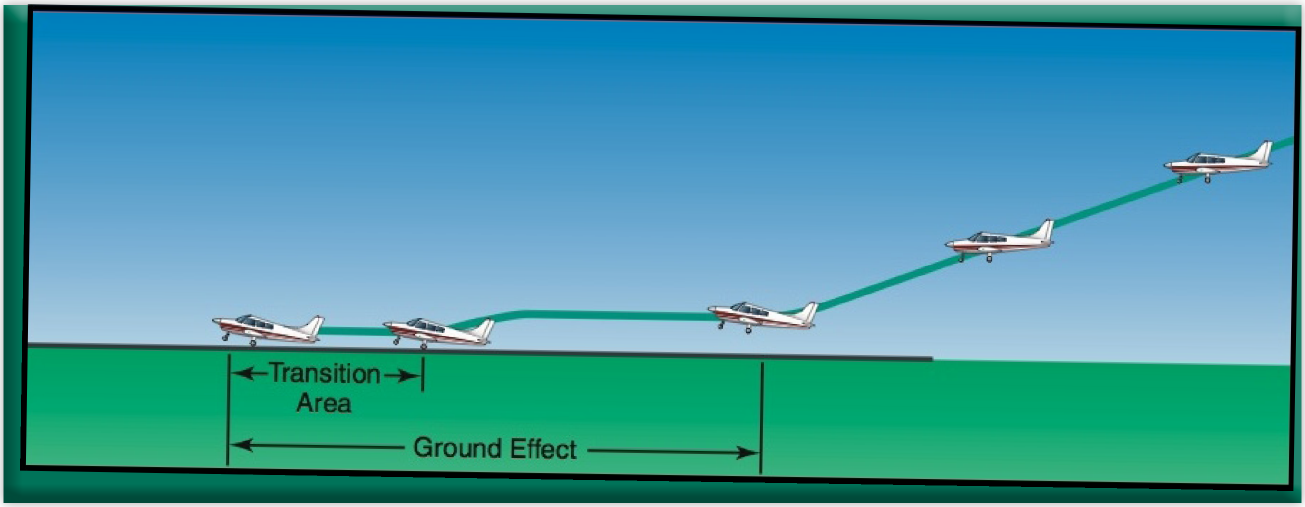


Figure 1.2: During landing, aircraft may experience ground effect once they are within 1/2 a wingspan of the ground.

FAA

Although ground effect creates a tricky situation, it does have its advantages. For example, if you are taking off on a short airfield your goal is to reach the perfect airspeed required for takeoff as quickly as possible. Ground effect can be used as an advantage in this situation to provide an increase in lift to get the aircraft off the ground quicker. Ground effect can also be used as an advantage when the airfield is made of soft material, such as grass, sand, or even a field covered in snow. As the aircraft is speeding down the runway, the soft surface creates more drag on the aircraft, which essentially slows it down. In this situation, the goal is to get the aircraft off the ground as quickly as possible, thus reducing the drag created by the wheels. To do this, pilots keep the nose of the aircraft as high as possible until they are in the air, when they can then ease the nose down while keeping the wheels in the air. Because of the drag and quick takeoff, the speed of the aircraft is relatively slow, but ground effect will enable the pilot to keep the aircraft in the air as they build up enough speed to climb safely out of ground effect. As you can see, when pilots understand ground effect, they can use it as an advantage in different situations.

Did You Know?

The Russian Ekranoplan was designed to fly only in ground effect. This aircraft never gets higher than a few feet off the ground. This design allows the aircraft to carry more cargo than would normally be possible if it flew at the same altitude as other cargo aircraft.

The Russian Ekranoplan on display in a park in Moscow, Russia.
Colorshadow/Shutterstock

AOA and Safety

In April 2011, an experimental Gulfstream G650 was making preparations for a test flight using only one engine at Roswell International Air Center in Roswell, New Mexico. During takeoff, the AOA was raised over the targeted level. The right wing stalled, and the aircraft rolled on the runway. The aircraft caught fire, killing all four crewmembers. During the National Transportation Safety Board's investigation, it was determined that the calculations for ground effect were flawed, and the speed at which the aircraft was attempting takeoff was too low. The AOA was raised too high, and the ground effect miscalculation caused the crash.

A Gulfstream G650 in flight.
Rob Hodgkins/Wikipedia Creative Commons

This lesson covered the forces needed to achieve flight, and some situations that require the pilot to consider and control those forces. The next lesson will examine aircraft design.

CHECKPOINTS

Lesson 2 Review

Using complete sentences, answer the following questions on a sheet of paper.

1. What are the four forces of flight?
2. What are two factors that affect the amount of lift an aircraft experiences?
3. How do aircraft designers combat the three types of parasite drag?
4. Why do vortices become visible during humid days?
5. What happens to vortex strength when the speed is increased?
6. What methods do pilots use to avoid wake turbulence?
7. What causes ground effect?
8. When does ground effect come into play?

APPLYING YOUR LEARNING

9. Why do you think it's important to understand the forces of flight if you plan on becoming a pilot?