Session 9
Landing

1.0 Definitions

Descent: moving from the cruising altitude to just above the runway.

Approach phase: The point where the pilot guides the airplane around to join the airport traffic pattern and lowers the landing gear and the flaps.

Traffic pattern: an invisible path in the sky around runways that pilots use to smooth traffic flow

Flare: the process of increasing the angle of attack of the wing and its lift. The purpose of the flare is to arrest the sink rate of the airplane just above the runway.

Rollout phase: starts when the plane touches down and ends when it stops rolling.

2.0 Introduction

The landing process has three distinct steps or phases: the approach, the flare to touchdown, and the ground roll after touchdown. Most of the math in this session is simply a variation of what was already described in the sessions on lift, drag, takeoff, and descents.

3.0 Theory

3.1 Descents

The technical look at descents is exactly the same as that for climbs except that the excess thrust is a negative value and therefore gives a negative climb rate. Although descents are not part of the landing session video, it is useful to understand the basic methods used to get down to the airport vicinity.

Consider yourself flying at cruising altitude until you see the runway below. If you simply push the plane into a dive straight for the runway and watch what happens, you'll see the airspeed increase very rapidly. That is because from the moment you push the nose of the airplane downhill, you get the extra thrust due to the weight of the aircraft. This was discussed in more detail in the previous sessions on drag and climb performance. The thrust force was set to exactly cancel the drag force during the level cruise, but that balance is upset in the dive.

You may have guessed that a steeper dive generates a greater thrust-due-to-gravity, and therefore gives a faster acceleration and a higher diving speed. This kind of high speed descent may create a problem. By doing this, you might either overspeed the plane by diving too steeply, or, more likely, end up right near the runway with too much airspeed.

You can have a real problem if you try to land with too much speed on the plane. One problem is that a fast vehicle of any kind is more difficult to control than a slow one. Another problem is that if you land fast, then you'll need more runway to stop.

If you fly near the airport and just push over, you'll end up too fast. Instead, pull the throttle back to idle when pushing over. By reducing the engine's thrust force, you can cancel out the extra thrust force from gravity. Reducing the thrust reduces the tendency to speed up in a descent. You still could fly too fast by nosing over *too* much, but it *is* easier to keep things under control this way.

There is another way of descending that you have already experienced in an airliner. Airline pilots fly along at cruise altitude until they're about 100 miles away from the destination airport. At that point you may hear the plane's engines reduce power slightly.

At the same time the captain will nose over so the speed doesn't change at all. Of course the plane will start descending because it's now pointed downward. This kind of descent begins long before you see the airport and can take 20 or 30 minutes.

To summarize descents, there are several ways of getting down: You can drop down steeply with idle power and high speed, or descend gradually with partial power and moderate speed, or descend by nosing over to a high speed with full power.
Whichever way you get down, the descent phase is complete when you're close enough to the airport to prepare to land.

3.2 Approach

The next step, called the approach phase, is the point where the pilot guides the airplane around to join the airport traffic pattern. Sometimes pilots fly "straight-in" approaches rather than fly in a pattern. This is the usual airline approach. To be sure of being over the runway with just the right combination of speed, altitude and sink rate, the pilot must be considerably more precise when flying the approach as compared to descending. While in the approach phase, the pilot also has to lower the landing gear and the flaps.

Figure 9.1 The Approach

All of the detailed procedures the pilot must follow in the approach phase are designed to do one thing: get the plane into position for the landing flare. To accomplish a safe flare, the plane must be within a range of values for speed, sink rate, and height above the runway. This "window" of numbers must be consistently attainable. To help the pilots be consistent, the approach phase is broken into several steps such as first getting to a specified speed, then lowering the gear, then lowering partial flaps, then slowing to another speed and so forth.

Part of the video discusses the invention and application of flaps. Review the lift discussion in Session 3 where the lift is affected by the wing's velocity, angle of attack and curvature. To get lift at the normal flying speed, the wing has a little bit of curvature and the pilot flies with a little angle of attack. To land, the pilot would want to slow down. To fly slower and still create the same lift, the pilot has to increase the angle of attack. This simple procedure works for typical, light aircraft because they have a lot of wing surface that allows them to fly very slow.

The stall speeds are faster for heavier aircraft than for light ones. The reason for this is the ratio of the weight (w) compared to the wing area (S). This ratio (w/S) is called the "wing loading." A sheet of paper (with a lot of area compared to its weight) will easily be lifted by a gentle wind, but a (bound) pad of paper will not because it weighs 50 or 100 times as much. This is the principle of wing loading and is applied to minimum flying speed for heavy and light aircraft. A typical general aviation aircraft (such as the Cessna 172) may have a wing loading of only 11 lbs/ft^2 and a typical airliner may be more like 120 lbs/ft^2. This yields a considerable difference in minimum flying speed.

To further illustrate this idea, consider a simple wing that, due to its cross-sectional shape and maximum angle of attack, has a maximum lift coefficient, C_{Lmax}, of 1.6. We can use the definition of C_L to calculate the minimum flying speed for various wing loading ratios:

Since *by definition* $C_L = 2w/\rho V^2 S$, then

$$V_{min} = [2/\rho C_{Lmax}]^{1/2} \times [w/S]^{1/2}.$$

Picking the standard sea-level value of .002377 for density (ρ), we can calculate the minimum speed for the Cessna as

$$V_{min} = [2/(.002377 \text{ x } 1.6)]^{1/2} \times [11]^{1/2} = 76 \ ft/sec$$

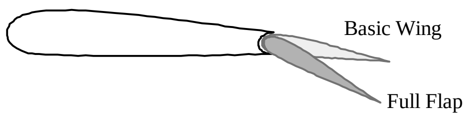
Using the same maximum C_{Lmax} and density, the effect of the higher wing loading is a stall speed of:

$$V_{min} = [2/(.002377 \text{ x } 1.6)]^{1/2} \times [120]^{1/2} = 251 ft/sec$$

This considerably higher stall speed leads to higher landing speeds and to two problems; more difficult handling as the pilot tries to precisely guide the aircraft at high speeds, and greater runway requirements for the ground roll.

To get slower stall speeds, the first idea may be to decrease the wing loading by putting on a much larger wing. A modern transport would look unusual if the wing was four or five times its current size. More importantly, it would have huge amounts of drag and would therefore fly very slowly. Designers had to go back to Newton's laws. They knew that they could use more curvature on the wing to create more lift at lower speeds, but then, they would have too much drag at high speeds. This drag discussion was covered in Session 4.

Of course, the answer was the development of flaps that could be used to change the camber (curvature) of the wing only when it was desired. Flaps don't weigh much and are very useful for increasing the value for C_{Lmax} anywhere from 20% to 60% (Figure 9.2). The advantage in decreased stall speed can be calculated using the previous equation.



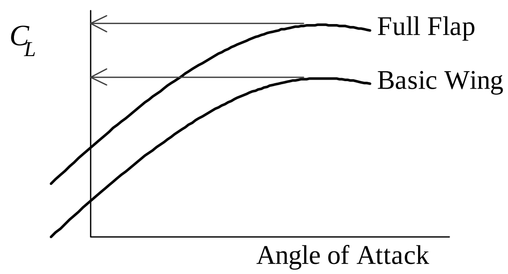


Figure 9.2

To ensure a smooth flight, most flight manuals call for a series of steps where the pilot incrementally extends the flaps, changes speed, and steers the plane around until it's lined up with the runway about 50 ft. above the ground and ready for the next phase, the flare.

3.3 Flare

The landing flare is the simplest to talk about, but the most difficult to do, and takes a lot of practice to be good at. The flare procedure goes something like this: the plane is approaching the runway at 80 mph on a 3 degree downhill slope (also known as the glideslope). Once in this position the pilot begins the flare about 50 feet above the runway by pulling on the wheel to smoothly increase the angle of attack and the lift of the airplane. This extra lift stops the plane's descent. This increase in angle of attack (and lift) from the approach to the flare is illustrated below.

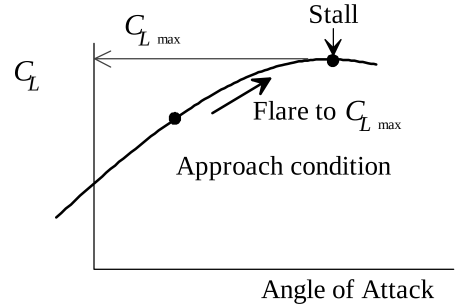


Figure 9.3

While doing this, gradually decrease the thrust to idle. With no thrust, the plane can't sustain flight a foot above the runway because the drag force acting on the plane's mass wants to decelerate it. Typically what a pilot will do is let the plane decelerate all the way to stall speed and gradually sink the last foot. The pilot's timing is crucial. The pilot has to judge just when and how much to pull the wheel and throttle. Depending on its size, speed, and handling characteristics, each plane has its own method.

Figure 9.4 The Flare

If the pilot pulls too aggressively, then the plane might "balloon up" back into the air and might even come crashing back to the ground if he doesn't react quickly. To recover from this situation, the pilot would have to add power to keep the plane from slowing and/or sinking too quickly. If the pilot doesn't pull enough during the flare, then he won't stop the sink rate, and the plane might hit the ground with the nose gear first or too hard.

Figure 9.5 The Balloon

Another complicating factor is turbulence. A gust of wind can upset any part of the approach or flare phase. It’s just like riding a bike or driving a car with precision - the faster you're going, the harder you have to work at it (see Suggested Activities for a demonstration of this).

One of the characteristics of a flare is that you pass by a lot of runway before touching down. If you point at the end of the runway during the approach but level off just above the runway, then you'll be flying along it, passing it by (Figure 9.6(a)).

This is acceptable for most kinds of flying because the runways are long. But suppose you don't have a long runway? Suppose you want to land on an aircraft carrier? There's no room to flare. The pilot flies the airplane straight onto the ship with a pretty high sink rate, (Figure 9.6(a)). Eliminating the flare gives the pilot pinpoint landing capability, but every landing is a hard "controlled crash." All carrier capable aircraft are built with a super strong structure and landing gear so they can slam onto the deck without being destroyed. Of course, the aircraft do have limits on how much sink rate they can handle.

3.4 Rollout

The last part of the landing, the ground roll, is least susceptible to pilot technique and so it is easiest to determine using Newton's Laws. The forces are similar to those for the session on takeoff performance.

Once the wheels touch, the wing doesn't have to support the aircraft's weight any more, so the pilot can feel free to decrease the angle of attack and speed as quickly as he wants to. The next task is decelerate the airplane to a full stop. To get an idea of the ability to slow down, go to Newton's second law, $F = ma$. Since we're looking for a deceleration, a should be negative. This means that to get the most possible deceleration, we would like the largest forces possible in the negative (or drag) direction and the smallest mass possible. Since we can't change the mass of the plane on most flights, we need to concentrate on the decelerating drag forces. To create drag forces, we have the brakes, the air, and the engine.

Brakes generate a drag force by converting the momentum of the plane into heat. Calculating the drag force they generate is simple: The braking drag is the braking coefficient μ times the weight on the wheels. μ decreases if you're braking on snow or ice (μ= .25), but is more or less a constant number for normal tires on normal, dry runways (μ=.75). In the takeoff session, μ was used to illustrate brakeless rolling friction and is typically about .05.

A class experiment to illustrate the concept of friction coefficient was discussed in the teacher's guide in Session 4 (Drag). Technically, the experiment discussed was for sliding friction - which is the case for a plane that is skidding, not rolling with braking force, as is normal.

If the wing isn't lifting at all, then the entire weight of the plane is supported by the wheels. A

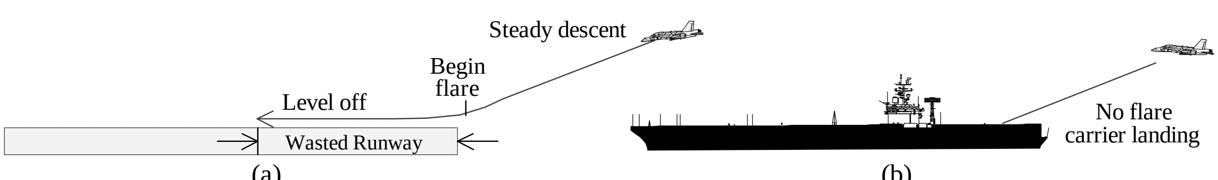


Figure 9.6

heavy weight on the wheels gives a lot of braking force to the plane. This wheel weight is often called the "reaction" force (R) in reference to Newton's third law. Some aircraft wings are still lifting after the plane touches down. This means that the brakes are not getting the full weight and are therefore not as effective since $F_{brakes} = \mu R$. As the plane slows further after touching down, the wing lift decays and the reaction force increases, thereby increasing the braking force.

Most of the time we're trying to minimize air drag force as much as possible, but to improve deceleration, we **like** drag. So, instead of keeping the airplane aerodynamically clean, the big heavy planes have spoilers (or air brakes) that pop out at touchdown. This desire for drag also encourages the use of full flaps for landing: planes can descend slower and steeper without speeding up if they have extended flaps. This extra drag is why planes <u>don't takeoff</u> with full flaps, although some takeoff with partial flaps. Some military planes even use parachutes called "drag chutes" to help slow them down. This is done only on military planes because it is expensive to have extra ground crew to pick up, pack and reload the chutes.

Another drag force can be created by the engine. Some propeller aircraft can be put in a "reverse" mode which changes the blade angle so it accelerates the air forward and slows the plane. These are a little complicated and more expensive to build, so not all planes have them. In a jet engine, they're called thrust reversers. Basically, a reverser "bucket" forces the exhaust towards the front in the direction opposite of the plane's motion (Figure 9.7). Newton's law about "equal and opposite reaction" shows that if the bucket forces the air to the front, then the air forces the bucket -and the rest of the plane- to the rear, the drag direction. Again, thhis can be seen on airliners and other transport aircraft because those types of planes need the most help to decelerate.

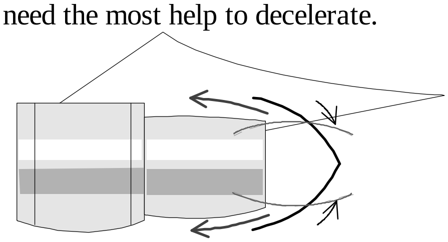


Figure 9.7 Bucket Swings

NOTE:

Session 4 of the text provides expanded information on kinematics.

Use Newton's second law to help see why it is important for large aircraft to use everything available to slow down the plane. Keep in mind that the biggest problem is the length of the runway. If its too short, then the plane can't fly in. To relate Newton's second law to required runway distance, review basic kinematics in class.

If desired, the kinematic relationship for any object can be developed as follows: From an initial speed (V_o) **assume** a constant deceleration (a) all the way to a stop. This can be illustrated graphically as follows:

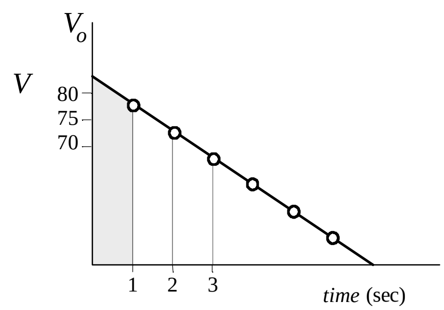


Figure 9.8 Kinematic Relationship

For the first second of travel, the average speed is 80 ft/sec which gives a distance of {80ft/sec x 1 sec} = 80 ft. For the next second, the average speed is 75 ft/sec which gives a distance of {75ft/sec x 1 sec} = 75 feet traveled and a cumulated distance of 80 + 75= 155 ft. This process can be continued step-by-step to get the total distance traveled. Note that for each time slice, the distance is the area under the curve.

A simple method is to recognize that the total <u>area</u> under the curve is the total distance traveled during the deceleration. Since the area of a triangle is $^1/_2$ *base x length*, then the distance $S = {}^1/_2 V_o$ *x time to stop*. Since we know $\Delta V/\Delta t = a$, then the time to stop is $t = V_o/a$. Combining gives the kinematic equation for distance traveled:

$$S = V_o^2/2a.$$

To apply this calculation to Newton's second law, determine the acceleration which gives $a = F/m$. Putting it all together gives a neat little equation for estimating ground roll distance:

$$S_{ground\ roll} = mV_{TD}^2/2\ F_{\mathrm{Drag}}$$

This says that the landing distance increases with the mass and the square of touchdown velocity (V_{TD}). The distance decreases as the drag forces go up. It's important to realize that this equation is valid only if the decelerating forces are constant. In reality, all of the forces in the drag direction change a little, so the equation is not exact.

The old biplanes were so light and landed at such low speeds that most of them didn't even need brakes - especially since they landed in grass fields that created lots of drag on the wheels. Approximate values to show a calculation of this for a Fokker Triplane are V_{TD} = 60 ft/sec, w = 1200 lbs, average drag from rolling wheels over grass = 90 lbs, average aerodynamic drag = 80 lbs.

$$S = [1200/32.2]\{60^2\}/2[90+80] = 395\text{ ft}$$

A big transport on the other hand, has a lot of mass and a high landing speed like 150 mph. The "velocity squared" effect shows that big planes would have huge landing distances unless they created a lot of drag. That's why we put big brakes, big spoilers, and thrust reversers on them. The landing distance equation is one of the primary reasons that we're trying to land as slowly as possible--- to shorten the required runway distance.

In reality, each of these drag forces changes a little during the ground roll. You can feel this when you get jerked around in your seat after touchdown. That jerking around is you experiencing Newton's first law: bodies in motion tend to remain in motion unless disturbed by an outside force. You are the body in motion. The seatbelt -which is attached to the rest of the plane- exerts an outside force on you that slows you down along with the plane.

4.0 Summary

To land an airplane you need to descend *to* the airport, reconfigure the airplane for landing then approach the end of the runway with the proper sink rate, flare the plane *just* over the runway to stop the descent then allow it to land in the last foot, and finally, decelerate the plane on rollout. Each step can be explained with basic physics.

It’s the test pilot's job to figure out the best procedures for descending, that means measuring the dive angle when thrust is reduced by 10 or 20%. During the approach it means figuring out the safest speed to fly each step of the way when the gear goes down and when the flaps go down. During the flare it means figuring out just when to throttle the engines and start the flare. Finally, a test pilot has to perform a series of ground rolls to see how much runway the plane <u>really</u> needs, not what is predicted from approximations.

5.0 Measures of Performance

1 What are the three phases of the landing process?

ANSWER
The approach, the flare to touchdown, and the ground roll after touchdown.

2 During the flare, why does the aircraft descend?

ANSWER
With the bulk of the thrust removed, the drag is greater than the thrust causing the aircraft to decelerate. As the aircraft decelerates, lift decreases causing the aircraft to descend to the runway.

3 What are three ways to create drag forces to decelerate?

ANSWER
1. Brakes, to generate rolling drag.
2. Airbrakes to increase aerodynamic drag.
3. Engine by "reversing" the thrust; that is directing the thrust forward.

6.0 Suggested Activities

Session 9
Landing

The difficulty of landing at high speeds can be demonstrated by having students ride bikes into a runway-like "chute" at different speeds. Like landing on a calm day, this is not much of a challenge if the rider is lined up with the chute long before he or she gets there, even at high speed. The task is made challenging (**especially** at high speed) if the rider follows a path that is laterally offset from the ideal path and is allowed to maneuver into position only immediately before entering the zone. This is like having a plane get bumped off-track by a wind gust.

To simulate a pilot flying in the weather and "breaking out of the clouds" just before touching down, the students can ride approximately towards the chute with eyes closed until someone shouts "BREAKOUT!" just prior to entering the chute. This simple exercise will illustrate the benefits of slow approach speeds in poor weather.