1 Energy Awareness and Energy Management

Riddle: What's the main difference between the sports car and the airplane?

Answer: If you speed up the sports car to about 75 miles per hour and pull back on the steering wheel, nothing very interesting happens.

When piloting an airplane, two of your most fundamental duties are (1) controlling the airplane's speed and (2) controlling its altitude.

Performing these duties would be easy if the airplane were equipped with ideal controls, so that you could (1) move a lever that would immediately change the airspeed by a few knots, with no change in altitude, or (2) move another lever that would immediately change the altitude by a few dozen feet, with no change in airspeed.

Alas, it is physically impossible to build an airplane with such ideal controls. One purpose of this chapter is to explain how *real* controls affect the airspeed and altitude of a *real* airplane.

For example, consider the seemingly simple maneuver of changing speed while maintaining a constant altitude. We will see that this requires a complex sequence of adjustments of several controls. There are two ways to deal with this maneuver. One way would be to discover (by trial and error) the required sequence of adjustments, and perform that sequence by rote forever after. A far easier and better way is to understand the fundamental relationships, so that the proper sequence seems logical and obvious.

Understanding how the airplane *really* responds to the controls makes your flying not only easier, but safer as well.

Generally, a pilot who tries to control airspeed and altitude separately winds up controlling one or the other rather poorly. Usually it is the airspeed that suffers. All too often, the airspeed gets too low, whereupon the wing stalls and the pilot rather abruptly loses control. This is how the all-too-common stall/spin accident begins. You can stay out of this sort of trouble if you understand what the controls *really* do.

The key to understanding the relationship between airspeed and altitude --- and several other things --- is the concept of *energy*.

Energy is not a new or complicated concept. Most pilots understand that being "high and fast" is very, very different from being "low and slow"; the concept of energy just makes this notion a little more precise and gives it an official name.

Good pilots think about energy all the time. The more critical the situation, the more carefully they evaluate the energy before reaching for the controls.

Once you grasp the basic concept of energy, you will be able to apply it in many ways, to many different situations. This is a big improvement over trying to figure out all possible situations one by one. Energy gives you the "big picture".

1.1 Energy Cannot Be Created or Destroyed

As illustrated in figure 1.1, there are four types of energy that are crucially important for airplanes, namely:

- potential energy, which is proportional to the airplane's altitude;
- kinetic energy, which is proportional to the square of the airspeed;
- the chemical energy in the fuel; and finally
- the energy left behind in the air as the plane passes through, stirring the air and leaving it slightly warmer.

There are of course other types of energy, but the four forms listed above are the ones pilots use all the time, so let's concentrate on them for now.[1]

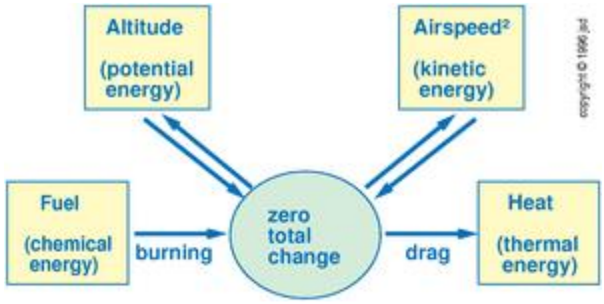


Figure 1.1: Total Energy Cannot Be Created or Destroyed

Energy has the remarkable property that it cannot be created or destroyed. Energy can flow from one region to an adjoining region, and it can be converted from one form to another ... but the amount of energy remains the same. This rule (which physicists call the law of conservation of energy) is not one of Newton's laws; it was not even known in Newton's day.

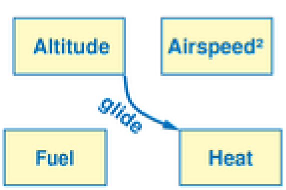
Consider the analogy with freezing water: liquid water can be converted to ice and back again, yet the amount of H_2O doesn't change in the process. Similarly, if some water leaks away and we lose track of where it is, the number of H_2O molecules hasn't changed.

Similar[2] notions apply to energy, as illustrated in figure 1.1. Fuel energy can be converted to altitude; altitude can be exchanged for airspeed; altitude can be cashed in to pay for drag; et cetera. The amount of energy doesn't change. The energy is just converted from one form to another.

Some of these energy conversions are irreversible. Fuel burn, for example, is a one-way street; we cannot (alas) operate the engine backwards and replenish the fuel supply. Similarly, when energy is dissipated by drag, that energy can never be recaptured in a useful form.

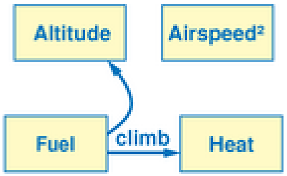
The airspeed and altitude together are called the *mechanical energy* . Engine power increases the mechanical energy, while dissipation decreases the mechanical energy.

1.2 Energy Conversion



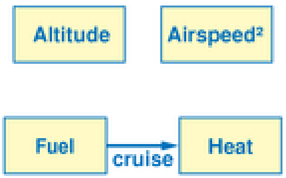
Altitude is being cashed in to pay for drag. The airspeed is not changing, and no energy is being taken from the fuel tank.

Figure 1.2: Energy Conversion -- Glide



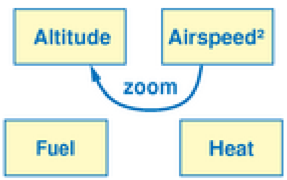
Fuel is being consumed to pay for drag and purchase altitude.

Figure 1.3: Energy Conversion -- Climb



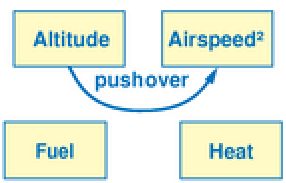
Fuel is being consumed to pay for drag. Altitude and airspeed are not changing much.

Figure 1.4: Energy Conversion – Cruise



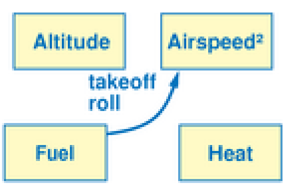
If you pull back on the yoke, the airplane will slow down and ascend. If you do it quickly enough, drag will not have time to consume very much energy, nor will the engine have time to convert very much fuel.

Figure 1.5: Energy Conversion – Zoom



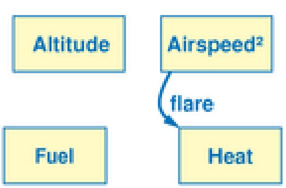
Conversely, if you push forward on the yoke, the airplane will speed up and descend. Once again, if you do it quickly enough, drag and engine power will not affect the energy budget very much.

Figure 1.6: Energy Conversion – Pushover



During the early part of the takeoff roll, drag is negligible. There is no change in altitude, so virtually all engine power goes toward building up airspeed.

Figure 1.7: Energy Conversion – Initial Roll



An important conversion is the flare maneuver, which occurs at the end of every flight. It is possible to maintain altitude without using the engine, by gradually cashing in airspeed to pay for drag.

Figure 1.8: Energy Conversion – Flare

Figure 1.2 through figure 1.8 show several examples of how one form of energy can be converted to another. We now investigate energy-conversion processes in a little more detail.

1.2.1 Converting Speed to Altitude and Back

An airplane (like any other object) has *potential energy* proportional to its altitude. Every increment of altitude represents an increment of energy. Similarly, any moving object has *kinetic energy* proportional to the square of its speed. We can easily convert back and forth between these two forms of energy. A roller-coaster is a well-known[3] example of this, as illustrated in figure 1.9.

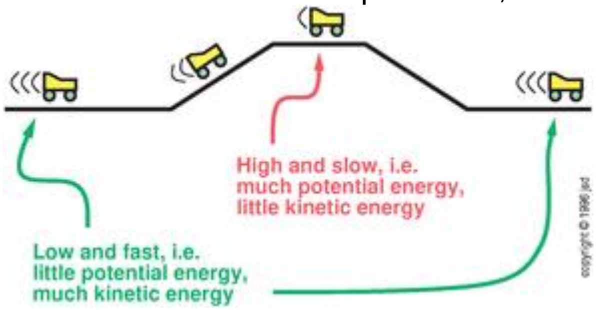


Figure 1.9: The Law of the Roller Coaster

At the left of the figure, we have a roller-coaster at a low altitude, moving quickly. In the middle of the figure, the roller-coaster has a higher altitude, but much less speed. At the right of the figure, the roller-coaster has returned to the lower altitude and regained its speed.

Since the roller-coaster carries no fuel and has very little friction, potential energy (altitude) and kinetic energy (speed) are the only forms of energy we need to take into account.

Here is the law of the roller-coaster:

Conversion factor = 9 feet per knot, per hundred knots

This law applies to airplanes, roller-coasters, or anything else that converts potential energy to or from kinetic energy. The altitude gain is proportional to (a) the amount of airspeed loss times (b) the average airspeed during[4] the maneuver. Let’s apply this to a couple of examples: if you are cruising straight and level at 201 knots, and you pull back on the yoke, when you reach 200 knots you will have zoomed up 18 feet. If you started at 101 knots and pulled back to 100 knots (once again a loss of one knot) you would only gain 9 feet.

This rule applies in any situation where friction can be neglected. The conversion factor, 9 feet per knot per hundred knots, is just the reciprocal of the acceleration of gravity[5] expressed in aviation units.

The two forms of energy --- altitude and airspeed squared --- are deeply related, even though they are measured in different units. We need a conversion factor (9 feet per knot per hundred knots) so we can convert from one set of units to the other.

1.2.2 Energy Per Unit Mass

Since we are about to start comparing these mechanical forms of energy with other forms, we must start paying attention to an additional detail: an object’s potential energy depends not only on its altitude but also on its mass. A 300-ton Boeing at any given altitude has 300 times more potential energy than a 1-ton Piper at the same altitude.

Similarly, an object’s kinetic energy is also proportional to its mass. A 300-ton object at any given airspeed has 300 times more energy than a 1-ton object at the same airspeed.

Since the mass of an airplane does not usually change much during the course of a maneuver, we can often simplify the discussion by ignoring the distinction between “energy per unit mass” and genuine “energy”. In cases where the distinction matters, I will remind you of it.

1.2.3 Converting Fuel to Altitude

Having understood the conversion between altitude and speed, let’s bring fuel into the picture. Each pound of fuel contains a certain amount of chemical energy. The engine allows us to convert this chemical energy to mechanical energy. Assuming typical engine efficiency, the fuel-to-altitude conversion factor is:

Typical conversion factor = 6300 foot-tons per gallon

That is, climbing 6300 feet takes 1 gallon more fuel than level cruising for the same amount of time, in a typical one-ton airplane. A heavier plane would require proportionately more fuel for the same climb.

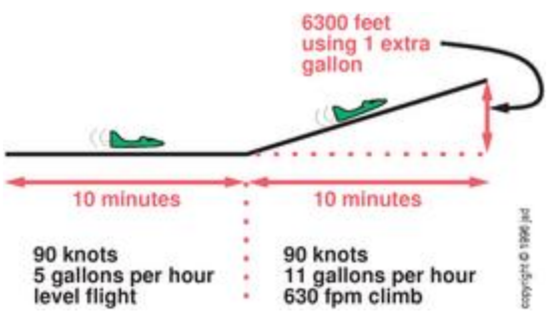


Figure 1.10: Converting Fuel to Altitude

To understand where this number comes from, and what it means, consider the experiment shown in figure 1.10. First we fly straight and level for ten minutes, maintaining 90 knots; we observe the fuel flow gauge is reading 5 gallons per hour. Then we open the throttle and climb for the same amount of time at the same airspeed; we observe a vertical speed of 630 feet per minute and a fuel flow of 11 gallons per hour.

The experiment tells us that in this particular airplane, climbing at 90 knots consumes 6 gallons per hour more fuel than level flight at the same speed. During 10 minutes (one sixth of an hour) the climb will eat up one extra gallon. The same 10 minutes at 630 fpm will gain us 6300 feet of altitude. The example plane weighs exactly one ton, so we get the conversion factor claimed above: 6300 foot-tons per gallon.

The exact value of the conversion factor will vary a little bit from airplane to airplane, depending on the efficiency of the engine, etc., but 6300 foot-tons per gallon is a good approximation in most cases.

To determine the fuel-to-altitude conversion factor for your airplane, you can (1) divide 6300 by the weight (in tons) of your airplane; (2) perform the experiment described above; or (3) work it out using the cruise-performance and climb-performance data in your airplane’s Pilot’s Operating Handbook (POH).

Here are the results for several airplanes from various manufacturers, using POH numbers:

Airplane	foot-tons per gallon
Two-place, carbureted, fixed gear, fixed prop	6172
Four-place, carbureted, fixed gear, fixed prop	6362
Four-place, fuel injected, retractable, constant speed prop	6410
Six-place twin, fuel injected, retractable, constant speed prop	6384

If the airplane were 100% efficient at converting fuel to altitude, the conversion factor would be higher --- but it is hard to build a really efficient engine with a reasonable size, weight, and cost.

1.2.4 Power versus Energy

Since fuel corresponds to altitude, fuel flow rate must correspond to rate of climb. Airline crews use this fact routinely: to make the transition from level flight to a 500 fpm descent at constant airspeed, they just retard the throttles until they see a certain reduction on the fuel flow gauges.

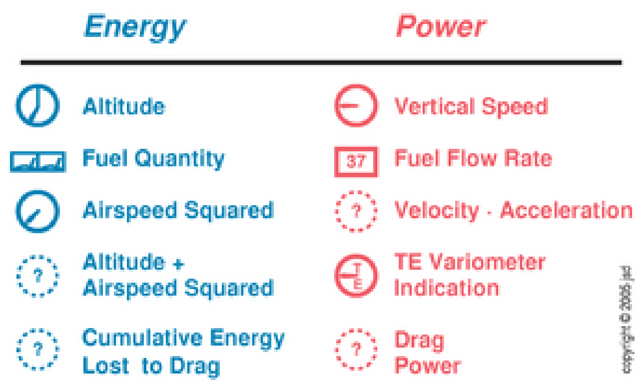
This notion of "energy per unit time" is officially called *power*. You don't want to confuse power with energy, any more than you would want to confuse a vertical speed indicator with an altimeter; the former indicates altitude *per unit time*, while the latter indicates altitude.

The airplane has instruments that measure most --- but not all --- of the relevant forms of energy and power. The energy gauges include the altimeter, airspeed indicator, and fuel gauges. These tell you how much potential energy, kinetic energy, and chemical energy there is on board.

The most common power gauges include vertical speed indicators and fuel flow gauges; these tell you at a glance how much power is flowing in and out of the potential and chemical reservoirs. Sometimes other power gauges are installed; gliders often have a "total energy variometer", which measures the rate of change in mechanical energy (potential plus kinetic) by measuring a combination of altitude change and airspeed change. Such a device is more useful than an ordinary vertical speed indicator for detecting updrafts, for the following reason: Inadvertently pulling back on the yoke will cause a positive indication on the vertical speed indicator (by the law of the roller-coaster) which might be confused with a real updraft; pulling on the yoke will cause *no* indication on the TE variometer.

Since the glider has no engine power to worry about, the TE variometer gives a reasonably complete picture of how much power is flowing in or out of the aircraft (updraft = power in; dissipation = power out). In an airplane with an engine and without a TE variometer, it is somewhat trickier to visualize what is going on.

Figure 1.11 summarizes this section by showing the various forms of energy and power, and some of the relationships between them. Gauges exist that will tell you some but not all of these quantities; you have to infer the others.



[Figure 1.11](#): Forms of Energy and Power

A reminder for the purists: a given quantity of gasoline contains a certain amount of chemical energy, period. In contrast, a given amount of altitude represents a certain amount of energy *per unit mass* of airplane. Therefore it is a slight oversimplification to suggest (as in figure 1.11) that the fuel gauge and the altimeter measure exactly the same thing, but it there is no harm in it if the mass of the airplane isn't changing. Similar remarks apply to the airspeed indicator.

1.2.5 Drag and the Power Curve --- Introduction

The time has come to bring drag into the picture.

The power dissipation due to drag is equal to the drag force times the airspeed.[6] Power is energy per unit time, which should not be confused with energy itself.

The distinction between energy and power is emphasized in the following analogy:

Altitude (energy) is like money in the bank. You pay the cost of climbing to altitude only once. If desired, you can cash in the altitude energy to do useful things.

Drag (power) is like rent; you have to pay a certain amount of energy per unit time for the privilege of flying the airplane through the air. That energy can never be recovered.

The amount of drag --- the amount of rent you have to pay --- depends on your airspeed[7] in a complicated way. The relationship is shown in figure 1.12, and is called the *power curve*.

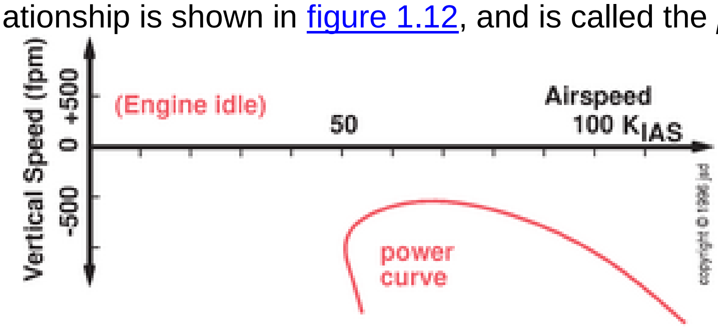


Figure 1.12: Power Curve (Engine Idle)

(You may be more familiar with this curve in an upside-down version called the "power required" curve. The orientation given here is preferable, for the following reason: Airplanes don't have "power required meters" but do have vertical speed indicators. Therefore this orientation is more meaningful in the cockpit. Also note that drag contributes a negative amount to our power budget, in contrast to the engine which contributes a positive amount.)

In the figure, airspeed is labelled in Knots of Indicated Air Speed (K_{IAS}). A knot is a nautical mile per hour, as discussed in section 14.2.2. The meaning of indicated (versus true) airspeed is discussed in section 2.12.

This figure applies to straight-ahead gliding flight. The engine is producing zero power; for any particular airspeed, the airplane will descend at the rate specified by the power curve. Altitude --- i.e. gravitational potential energy --- is being cashed in to pay for the frictional losses.

The traditional units for the vertical axis in this figure would be horsepower, but I have used feet per second instead. This is intended to clarify the equivalence of all four forms of energy by measuring them in a common set of units. We have seen how to think of airspeed in terms of altitude (9 feet per knot per hundred knots) and also how to think of fuel in terms of altitude (6300 foot-tons per gallon), so it is only logical that power should be measured as vertical speed; that is, altitude-change per unit time.

The terminology and basic applications of the power curve are presented in the next couple of paragraphs; some more advanced applications will be presented in section 7.5.

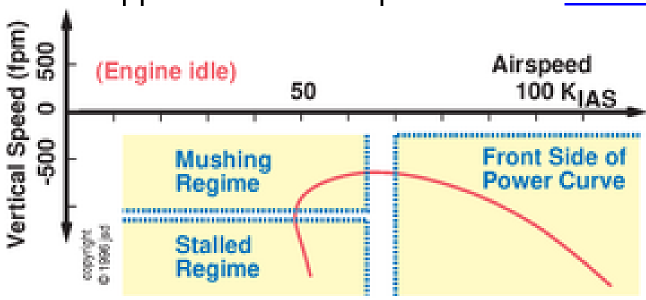


Figure 1.13: Power Curve --- Three Regimes

As shown in figure 1.13, the power curve is divided into three regimes. The right-hand part of the curve (from moderate airspeeds on up) is called the *front side of the power curve*. Normal cruising flight is conducted in this range of airspeeds.

In this regime, the faster you go, the more power is consumed by friction. This is completely unsurprising --- everybody knows that moving an object through the air quickly takes more force than doing it slowly. You can see in figure 1.13 that if you glide at a very high airspeed, you will have a large rate of descent.

What is less obvious to non-pilots is that at low airspeeds there is another regime with very high drag. This is called the *mushing regime*, and is labelled in the figure. The logic here is that it is more efficient to visit a lot of air and yank it down gently than to visit a small amount of air and yank it down violently. In this regime the airplane must fly at a high angle of attack in order to support its weight. This creates strong wingtip vortices that in turn produce huge amounts of induced drag, as discussed in section 3.12.3. Therefore if you are in the mushing regime, flying more slowly causes more descent rate, as can be seen in figure 1.13. This is quite unlike cars --- a car moving slowly incurs very little frictional loss. Of course, cars don't need to support their weight by pulling down on the air.

The dividing line between the mushing regime and the front side of the power curve is the highest point on the power curve. At this point, the airplane can fly with the minimal amount of dissipation; this is the "low-rent district". The airspeed where this occurs is called the best-rate-of-climb airspeed and denoted V_Y.[8]

Finally, we consider the extreme lower-left part of the power curve. This is called the *stalled regime*, as indicated in figure 1.13.[9] Flight in this regime is very, very peculiar.

The mushing regime and the stalled regime are collectively referred to as the *back side of the power curve*.

Life would be simpler if manufacturers would explicitly show the power curve somewhere in the POH, but they don't. You have to figure it out for yourself. Fortunately, the general shape of the power curve is more-or-less[10] the same for all airplanes, so the concepts discussed here are very widely applicable.

1.2.6 Rates of Energy Conversion

An airplane can very rapidly and efficiently convert airspeed to altitude, and vice versa. Because of this, these two forms of energy are often considered together, and are collectively referred to as the mechanical energy.

In contrast, it is difficult to convert fuel to mechanical energy quickly, and it is difficult to dissipate large amounts of mechanical energy via drag quickly (especially while maintaining a safe airspeed).

A rapid conversion of airspeed to altitude is called a *zoom* --- a fairly common maneuver.[11] You should always be careful when performing a zoom, because if the airspeed gets too low there could suddenly be very unpleasant consequences.

The airplane's ability to convert airspeed to altitude and back again is the key to many aerobatic maneuvers. There is no way you could perform a loop using engine power alone; you have to zoom. Bob Hoover's airshow routine typically closes with a spectacular energy management demonstration. After shutting down the engine, he performs a series of complex aerobatic maneuvers, including an eight-point roll and a hammerhead.[12] He then returns for landing and coasts to the reviewing stand, all without restarting the engine. It is quite a fascinating lesson in pilot technique.

1.3 Effect of Controls on Energy

The previous section introduced the main forms of energy that affect flight. The next step is to discuss how the pilot can control the energy in various ways. This section doesn't introduce very many additional concepts; it mainly just combines and applies the concepts introduced previously.

We continue to use the analogy between energy and money. Therefore, deciding how much power should flow from one reservoir to another is called the power budget.

1.3.1 Power Budget --- Using the Engine

Figure 1.14 shows how engine power affects the power budget.[13] The bottom curve applies when the engine is operating at 1700 RPM, the middle curve applies at 2000 RPM, and the top curve applies at 2300 RPM.

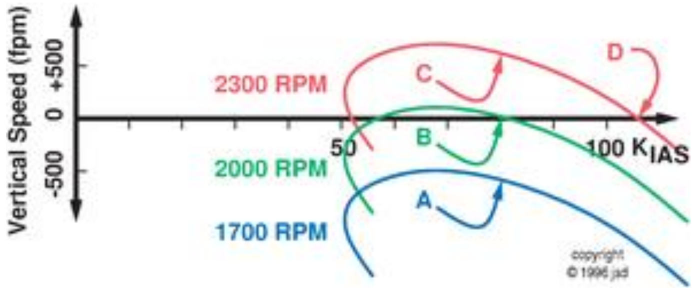


Figure 1.14: Power Curve (Various Engine Power Settings)

Point *A* indicates a 500 fpm descent at 80 knots. Point *B* indicates level flight at the same airspeed, and point *C* indicates a 500 fpm climb still at the same airspeed. The rule is simple: if the engine produces more power, the airplane will descend at a lesser rate or even ascend.

Point *D* corresponds to level flight at 110 knots. The power setting is the same as at point *C* --- but the energy that was being used to purchase altitude (point *C*) is now being used to pay for the higher drag at the new airspeed (point *D*). If engine power exactly equals frictional losses, the airplane will stay level --- fuel energy is being used to pay for the friction.

The numbers in this example are consistent with a rule of thumb that applies to a wide range of light aircraft: starting from level flight, to set up a 500 fpm descent,

- Reduce power by 300 RPM (for a fixed-pitch prop), or
- Reduce power by 3" of manifold pressure (for a constant-speed prop).

This rule works surprisingly well over quite a range of different makes and models. Make a point of learning whichever version of this rule applies to your airplane. It is a big improvement over blindly guessing at throttle settings.

1.3.2 The Effects of the Throttle

I make sure all my students really understand the effects of a power change. In the first or second lesson, we get the airplane trimmed for straight and level flight (using a moderate power setting). We then push the throttle a little more open. The student may be expecting that the airplane will respond by speeding up, just like a car. But airplanes are not the same as cars! In most airplanes (including all the common trainers) the airplane will actually slow down slightly.[14] This experiment --- observing how power changes affect the trim speed of the airplane --- is one of the first things I do not just for students but also for myself when I am learning to fly a new make & model of airplane. (It is also important to learn how flap extension affects the trim speed, and how the flaps and power interact.)

The throttle[15] controls power. What could be simpler? The throttle controls power. (Remember, power is energy per unit time.)

There are three things this power could be used for:

1. Power is needed to overcome drag. Flight at speeds above or below V_Y requires more power than flight at V_Y.
2. Climbing requires more power than level flight, other things being equal.
3. Speeding up requires more power than unaccelerated flight along the same path.

Non-pilots commonly think engine thrust will cause the airplane to speed up, but usually that's not what happens. Although the airplane is being pulled forward, the trim mechanism notices what is going on and immediately converts the new energy to altitude. Therefore the throttle can be reliably used to control up/down motion. As discussed in chapter 6, this is the normal, natural aerodynamic behavior.

Of course, if you defeat the trim mechanism, all bets are off. For instance:

- During the takeoff roll, the airplane is not free to move in the vertical dimension, so the trim has no effect. Therefore (in this special situation) energy coming from the engine is converted to speed, not altitude.
- Similarly, suppose your autopilot is manipulating the yoke so that the airplane maintains level flight. This means the natural aerodynamics of the trim mechanism is irrelevant. When you open the throttle (in this special situation) the added energy will be converted to airspeed, not altitude. Note that the autopilot has to move the yoke to make this happen --- so we can reasonably say that the airspeed change is "caused" by the yoke movement more directly than it is "caused" by the added power.

I reiterate that in flight, if you (and the autopilot) leave the yoke and trim alone, opening the throttle just makes the airplane climb. If you want to change airspeed without an altitude excursion, you will need to adjust the throttle *and* the yoke, as discussed in section 7.2.

A car, of course, will speed up when you open the throttle. But this has got nothing to do with the behavior of an airplane in flight.

An airplane is not the same as a car. Cars don't have trim. Cars aren't free to move in the third dimension.

Now that we understand the effects of opening the throttle, the effects of closing the throttle should be no surprise. The airplane will maintain its trim speed (or possibly speed up very slightly) and descend. This is easy to understand in terms of energy; compare points B and A in figure 1.14. If engine power is reduced, the only way to pay the rent is to cash in altitude energy at a steady rate.

1.3.3 The Effects of the Yoke

Now let's do a slightly different experiment: pulling on the yoke. As before, start with the airplane nicely trimmed in straight and level flight. Then pull the yoke back a little ways and hold it there. What happens next? Several things will happen, on various time-scales:

- The pitch attitude will change. This is important, but will not be discussed here.[16]
- You will slow down. Think of this as the primary effect.[17] The new, lower airspeed will persist throughout the short term and the long term.
- There will be a short term effect and a long term effect on altitude. That is:
    - Because of the decrease in airspeed, you will zoom upwards. This is a short-term, one-time increase in altitude, according to the law of the roller-coaster. You are trading in kinetic energy, exchanging it for potential energy.
    - At the new airspeed, you will be operating at a new point on the power curve.
        - If this is a more-efficient operating point, you will get a long-term climb.
        - If this is a less-efficient operating point, you will get a long-term descent.

Let's clarify the long-term behavior by considering two versions of this experiment. In the first version, as illustrated in figure 1.15, the airplane is initially on the front side of the power curve --- cruising at 105 knots, which is definitely on the front side of the power curve. Pull back on the yoke a little, and hold it.

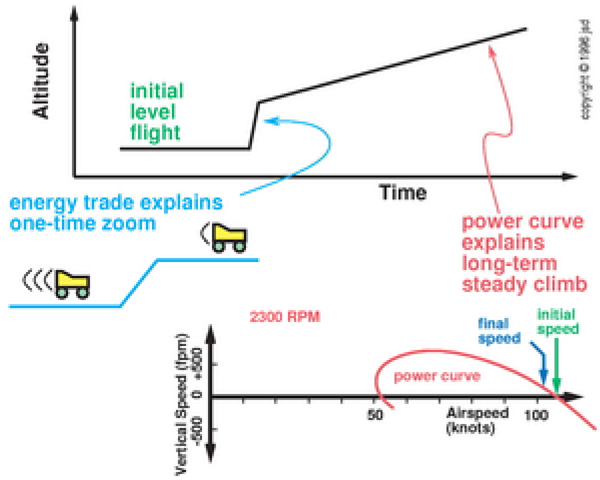


Figure 1.15: Pulling on the Yoke --- From Cruise

What happens to the airspeed and altitude?[18] The first thing that happens is that the airplane slows down from 105 knots to 100 knots. You should think of this as the primary effect of moving the yoke. This is a short-term *and* long-term effect.

As a first consequence of this speed change, the airplane will zoom up about 45 feet, according to the law of the roller coaster: 9 feet per knot, per hundred knots. This is a short-term, one-time effect.

As a second consequence of the speed change, the new speed sits at a more-efficient place on the power curve. Less power will be consumed by drag, so the airplane will ascend. (Remember we've kept the engine power unchanged.) The airplane will continue to climb at a steady rate for a long time.

The short-term altitude change is governed by the law of the roller-coaster, while the long-term altitude change is governed by the power curve.

So far this all seems pretty normal --- but the second version of the experiment is much more interesting, as shown in figure 1.16. Let's reconfigure the airplane for flight on the back side of the power curve --- say 58 knots. Trim the plane for straight-and-level flight, then pull back on the yoke a little and hold it there.

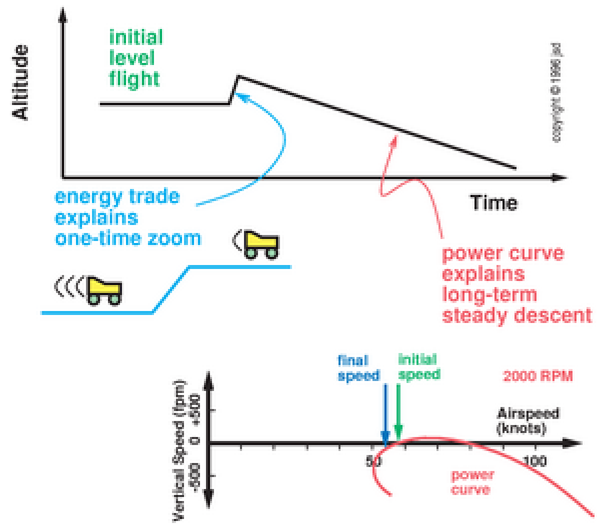


Figure 1.16: Pulling on the Yoke --- From Slow Flight

The first part of the story is the same: you will slow down. Let's say the new speed is 53 knots. As always, you should think of this as the primary effect: if you pull back on the yoke you will slow down.

The second part of the story is also the same: there will be a one-time increase in altitude. This time it will be about 25 feet. The zoom is less than in the previous case, because the initial airspeed was less.

The final part of the story contains the surprise: because the new airspeed represents a higher-drag (less-efficient) point on the power curve, the airplane will enter a steady descent. At the new airspeed, it will descend and descend and descend.

As always, the short-term altitude change is governed by the law of the roller-coaster, while the long-term altitude change is governed by the power curve.

This scenario (a short-term ascent followed by a long-term descent) is called a *zoom*.[19] It is the bane of student pilots when they start learning to perform landings. Starting from a low airspeed a few feet above the runway, they pull back on the yoke The airplane obediently zooms upward, then (alas) descends at a tremendous rate and makes an airplane-shaped hole in the runway.

Students who have not been taught the distinction between the short-term and long-term effects have a hard time figuring out this situation.

Note: this treacherous behavior (short term ascent followed by long-term descent) does not imply that the airplane is stalled or about to stall. As mentioned in section 1.2.5, the mushing regime is not the same as the stalled regime. In the mushing regime, induced drag is the culprit; stalling is a completely different issue, which is discussed in chapter 5.

Sometimes the mushing regime is called the "*regime of reversed control*", but this is not a very good term. The following table summarizes the actual effects of pulling back on the yoke:

	Front-side effect	Mushing effect	Reversal?
Airspeed	decrease	Decrease	no
Short-term altitude	increase	Increase	no[20]

Long-term altitude	increase	Decrease	yes

By two votes out of three, we conclude that the term “regime of reversed control” is not a good description of the mushing regime.[21]

1.3.4 Sizes of Energy Reservoirs

The following observation may help put into perspective the sizes of the various energy reservoirs. First, consider normal cruising flight: the energy in the fuel tank is enough to “pay the rent” (overcome drag) for several hours. Second, consider a power-off glide: starting from a reasonable cruising altitude, altitude energy can be cashed in to pay the rent for several minutes. Finally, consider the flare maneuver: it is possible to arrest a power-off descent and maintain level flight by cashing in airspeed for a few seconds.

To summarize:

You can pay for drag by cashing in fuel ... for a few hours.
You can pay for drag by cashing in altitude ... for a few minutes
You can pay for drag by cashing in airspeed ... for a few seconds.

So, we see that the available energy reservoirs have very different sizes.

This difference in sizes has many consequences, but the most important one is this: you cannot make large altitude corrections (only small ones) by borrowing from the airspeed reservoir.

That is, suppose you are a few feet below your desired altitude. The quickest way to get back up is to pull back on the yoke. You thereby cash in some airspeed energy to buy altitude, according to the law of the roller-coaster. On the other hand, if you try to go up some more by pulling back some more, you will very soon run out of airspeed.

The bottom line is: you should feel guilty about borrowing energy from the airspeed reservoir. There just isn’t very much energy there to begin with, and letting the airspeed get too low can have serious consequences.

The pros and cons of controlling altitude by borrowing airspeed are discussed in more detail in chapter 7.

1.4 Energy Management Strategy

The next step is to combine what we know about energy and develop general rules for energy management. Let’s consider the four situations depicted in figure 1.17.

In the figure, as we go from left to right the kinetic energy increases; similarly as we go from bottom to top the potential energy of the situation increases.

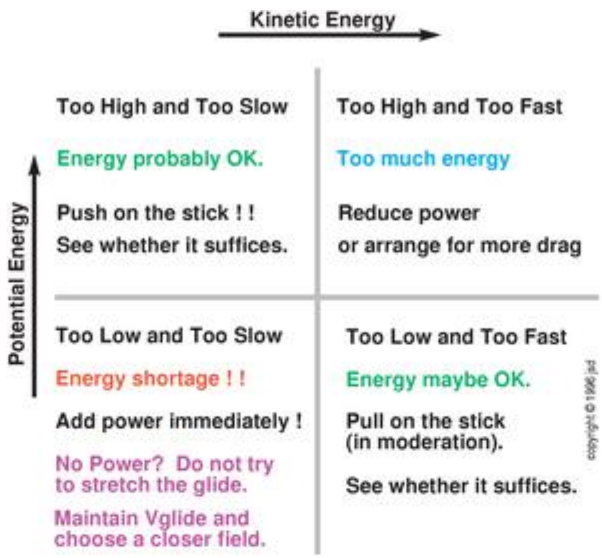


Figure 1.17: Energy Management --- Four Situations

Let's start by considering the situation in the upper-left corner: the altitude is a bit high and the airspeed is a bit low. If we're lucky, the total energy might be about right. Therefore, the obvious thing to do is to push on the yoke. That will get rid of some altitude by converting it to airspeed, which is basically what we want.

In the lower-right corner we have the complementary scenario: the altitude is a bit low and the airspeed is a bit high. Once again, if we are lucky the total energy might be about right. Therefore, the obvious thing to do is to pull on the yoke (in moderation). That will convert some of the excess airspeed into altitude, which is basically what we want.

The situation in the upper-right corner is more challenging: both the airspeed and the altitude are too high. Unlike in the previous two scenarios, we clearly have an energy problem: the total energy is too high. There is nothing you can do with the yoke that will make the altitude better without making the airspeed worse,[22] and vice versa, so we have to find something else to do. The first step is to retard the throttle, the sooner the better; every bit of power that the engine produces only adds to the energy problem. The other way to get rid of energy is to increase drag. This can be done by extending the landing gear, extending the flaps, slipping, et cetera. Over time, the increased drag will take energy out of the system, which is what you want. If drag is not taking energy out of the system fast enough, you may have to perform a 360 degree turn or something in order to buy some more time.

Finally, let's consider the lower-left corner of figure 1.17. In this case, both the airspeed and the altitude are too low. This is the proverbial coffin corner. You have an energy problem, and having too little energy is even worse than having too much energy. You should open the throttle immediately; this will (over time) convert some fuel energy into new airspeed and/or altitude.

If no power is available, do not try to "stretch the glide". There is nothing you can do with the yoke that will add new energy to the system; all you can do is minimize the loss by maintaining the canonical best-glide airspeed. Since you are too slow, push on the yoke to re-establish that airspeed. Since you are too low, choose a closer place to land.

Never try to stretch the glide.

Our discussion of how the yoke and the throttle are used together for energy management is continued in chapter 7.

1.5 Summary: Energy Management

Question: What makes the airplane gain altitude? Answer: four things:

- Updraft.
- Zoom.
- Less drag.
- More engine power.

The most common way of reducing drag is by selecting an airspeed closer to V_Y. (Of course it also pays to get rid of any extraneous drag, perhaps by retracting the flaps, retracting the landing gear, and/or reducing the amount of slip.)

Suppose you are on final approach for landing. You notice that you are below the glideslope. What should you do? Add power?? Pull back on the yoke?? --- *This is asking the wrong question.* The glideslope indication alone doesn't give you enough information to decide what to do.

You need to perceive the airspeed as well as the height. Think about your energy: potential energy plus kinetic energy. Being low and slow is very different from being low and fast.

Instructors: on final, ask your students "Are we high or low, fast or slow?" Make sure they evaluate the energy situation continually and correctly.

Altitude and airspeed tell you your total mechanical energy. In the short run there is nothing that will change the total mechanical energy; all you can do is use the yoke to trade energy back and forth between altitude and airspeed. The conversion factor is nine feet per knot, per hundred knots.

In the long run, the throttle (engine power) and the power curve (drag power) control the rate at which energy is entering and leaving the "airspeed plus altitude" system. To establish a long-term climb, add power and/or trim for a speed closer to V_Y. To overcome drag (in unaccelerated level flight) requires power. To climb (while maintaining constant airspeed) requires added power. To speed up (while maintaining constant vertical speed) requires added power.

The amount of energy in the airspeed reservoir is very small compared to the energy in the altitude reservoir, which is in turn very small compared to the energy in the fuel reservoir.

If you value your life, look at the airspeed indicator before pulling on the yoke. Looking at just one indicator (altitude *or* airspeed) for making a decision about just one control (yoke *or* throttle) is poor pilot technique and could well lead to a stall/spin accident. You must look at both indicators, size up the energy situation, and then decide what to do with both controls.

1

For instance, solar energy can produce updrafts and windshears. Sometimes the airplane's ability to extract energy from these is important, as discussed in section 7.5.7 and section 16.17.2.

2

The analogy between water and energy is only approximate. Water molecules can be created from scratch by chemical processes, for instance by burning hydrogen or hydrocarbons. Sometimes water-creating and water-destroying reactions are negligible, in which case we can treat water as being *approximately* conserved. Meanwhile, energy is always *exactly* conserved. There are no processes whatesover that create or destroy energy.

3

Langewiesche (reference 1) devotes an entire chapter to “The Law of the Roller Coaster”.

4

To be exact: Take the initial airspeed and final airspeed and average them.

5

... that is, g = 9.807 meters per second per second; $1/g$ = 8.8537 feet per knot, per hundred knots.

6

The relationship between force and power is discussed in more detail in section 4.5.

7

As we shall see, it would be more precise to say that the drag depends on angle of attack --- but airspeed is often a convenient stand-in for angle of attack, as discussed in section 2.12.

8

a more precise definition of V_Y will be given in section 7.5.

9

Section 5.3 gives a precise definition of stall, and section 5.3.2 explains why the power curve hooks back to the right in the stalled regime.

10

Section 7.6 explains the slight variations from plane to plane, and how to sketch the power curve for your particular airplane.

11

The reverse conversion, altitude to airspeed, is equally common but does not have a correspondingly colorful name.

12

A hammerhead involves flying vertically upward until the airspeed is practically zero, yawing the airplane 180 degrees to point the nose downward, and then retracing your steps vertically downward.

13

This is slightly idealized. See section 7.5 for more details.

14

The rare exceptions are discussed in section 6.1.4.

15

... in conjunction with the RPM control if you have a propeller governor.

16

Having a particular pitch attitude is rarely an end in itself. Instead, you should use it as a good means of controlling other things, such as angle of attack; see section 2.6 and section 2.10. Also note that abrupt movement of the yoke will provoke phugoid oscillations, as discussed in section 6.1.12.

17

The aerodynamics of how the yoke and trim govern airspeed is discussed in chapter 6.

18

Again, note that discussion of pitch changes is being postponed until section 2.6.

19

Some older books call it “ballooning”.

20

... unless you pull back very, very slowly, in which case the short-term ascent might be masked by the long-term descent.

21

Similarly, in the mushing regime, other controls (such as the ailerons) become less effective, but they do not reverse.

22

... in the short run, at least --- but see section 7.7.1.

2 Angle of Attack Awareness and Angle of Attack Management

If you want to go up, pull back on the yoke.

- If you want to go down, pull back a little more.
- If you want to go down real fast and spin around and around and around, just keep pulling back.

--- Aviation proverb.

2.1 The Importance of Angle of Attack

Angle of attack is a very important and useful concept. Most of the airplane's critical performance numbers are more closely related to angle of attack than to anything else. Let's explore what this means.

You've probably heard that it is good to fly the airplane "by the numbers". The question is, *what* numbers?

Suppose we wish to achieve the best rate of climb:

A)

You could try to control the airplane by reference to the "rate of climb" number shown on the vertical speed indicator. This is not recommended!

B)

It would be better to maintain V_Y, the nominal best-rate-of-climb speed, as shown on the airspeed indicator, and accept whatever rate of climb results. This is almost exactly the right idea.

C)

It would be even better to realize that the best rate of climb is achieved at a particular angle of attack. In particular, if the airplane is lightly loaded compared to what was anticipated in the handbook, the best rate of climb will be achieved at a lower speed than is reflected in the handbook's V_Y value.

This is not an isolated example. Many of the airplane's critical performance numbers are really angle of attack numbers:

- The stall occurs at a particular angle of attack.
- The smallest power-off descent rate occurs at a particular angle of attack.
- The best power-off glide ratio occurs at a particular angle of attack.
- The recommended "approach speed" is really an angle of attack recommendation.
- The best rate of climb occurs at a particular angle of attack.
- The best angle of climb occurs at a particular angle of attack.[1, 2]

Here is a summary of the main ideas that will be explained in this chapter:

- The airplane is trimmed for a definite angle of attack. The “pitch” trim wheel is really an angle of attack selector.
- Push/pull motion of the yoke can be viewed as an extension of the trim wheel --- just another way of controlling angle of attack. It is very difficult to stall the airplane unless you pull back on the yoke and/or apply lots of nose-up trim. This idea could save your neck.
- Outside visual references also provide information about angle of attack, if you know what to look for.
- The airspeed indicator provides quantitative information about angle of attack, when the airspeed is not too low. Correction factors must be applied to correct for nonstandard weight and/or *G*-loads.
- Configuration and power changes have minor effects on the trimmed angle of attack.

2.2 Definition of Angle of Attack

I will now explain what angle of attack is, why it is important, and how it is related to things a pilot can actually observe and control.

The basic idea is simple: the angle of attack is the angle at which the air hits the wing. The Wright brothers had only one flight instrument on their first airplane --- an angle of attack instrument. It was all they needed.

Their angle of attack indicator consisted of a stick attached to the wing, with a piece of yarn dangling from the front end, as indicated in figure 2.1. The yarn aligns itself with the relative wind.[3] The stick serves as a reference line, and also serves to locate the yarn in a region of air that has not been too badly disturbed by the wing.

Figure 2.1: Simple Angle of Attack Instrument

The angle between the stick and the yarn indicates angle of attack.

The exact alignment of the indicator stick relative to the airplane is not critical. The most elegant scheme is to orient the stick in the *zero-lift direction* so that zero angle of attack corresponds to zero coefficient of lift. That choice will be used throughout this book; see section 2.14 for a discussion of other possibilities.

Most aircraft do not have any instruments that give the you a direct indication of angle of attack. Surprisingly, many airliners and other aircraft that *do* have fancy angle-of-attack sensors don’t make the information available to the flight crew --- only to the autopilot. The bottom line is that most pilots have to use a few tricks in order to perceive angle of attack. We now discuss how this is done.

It turns out to be easier to maintain *some* constant angle of attack than to know precisely what angle of attack you’ve got. The strategy is summarized in the following outline.

1

--- There are several ways to maintain a constant angle of attack.

1.1

– The airplane is trimmed for a definite angle of attack (see section 2.3).

1.2

– You can perceive the angle of attack and regulate it by hand. To perceive the angle of attack, you need to compare the pitch attitude to the relative wind.

1.2(a)
– There are at least four ways to perceive the pitch attitude (see section 2.5).
1.2(b)
– There are a couple of ways to estimate the direction of the relative wind (see section 2.11).
2
--- You can use the airspeed and other considerations to decide if you are maintaining the *right* angle of attack (see section 2.12).

Now let's investigate each of the items in this outline.

2.3 Trim for Angle of Attack!

The simplest and best way to get the airplane to fly at a constant angle of attack is to *leave it alone!* An airplane, by its very structure, is trimmed for a definite angle of attack. The reason for this is discussed in chapter 6. Even a dime-store balsa-wood glider wants to fly at a definite angle of attack.

This concept is so important that it is the focal point of the first lesson I give student pilots, who sometimes arrive with the misconception that pilots must use great skill and continual intervention to keep the airplane under control. I trim the airplane for straight and level flight and then take my hands off the controls, demonstrating that the airplane will fly just fine for quite a while with no intervention at all. I emphasize a professional pilot does not grab the controls firmly and move them quickly; a real pro grabs them lightly and moves them smoothly.

The second lesson is this: I trim the airplane for a speed near V_Y, straight and level. I then roll the trim wheel back a little, which results in a decrease in the trim speed. It does not result in a steady climb. I explain that the trim wheel controls angle of attack, and that airspeed is related to angle of attack. Trim for angle of attack!

To make changes in the angle of attack, you should adjust the pitch attitude using pressure on the yoke, then trim to remove the pressure, as discussed in section 2.6.

Configuration changes can affect the airplane's preferred angle of attack. In a Cessna 152, 172, or 182, if you extend the flaps *while the engine is at a high power setting* or if you increase the power *while the flaps are extended* it will cause a nasty decrease in the trim speed. This is highly undesirable and dangerous behavior. This means that when you perform a go-around, the airplane tends to pitch up drastically and lose airspeed; to maintain control you need to push on the yoke while you retract the flaps and retrim. This pitch-up behavior is particularly treacherous because it is not familiar. The trim speed changes very little if you extend the flaps at low power settings, and/or change the power with the flaps retracted, so if you haven't recently performed many go-arounds or similar maneuvers you might be in for a nasty surprise.

For a typical Cherokee, extending two notches of flaps lowers the trim speed ten or fifteen knots. This is discussed further in section 5.5 and section 12.10. Increasing or decreasing engine power affects the trimmed angle of attack only slightly. As discussed in section 1.3.2, if you just reduce power the airplane should just descend. It should not slow down appreciably; in fact it will probably speed up a little.

An advanced lesson serves to demonstrate that constant angle of attack is not quite the same as constant airspeed. When the airplane is subjected to a high *G*-loading, as in a steep turn, the trim mechanism causes it to speed up, so that it can support the increased load at the same angle of attack. This is important, since (as discussed in section 6.2) it helps explain graveyard spirals, and why it is a bit tricky to recover from them safely.

Conclusion, valid when load factor = 1:

Trim for airspeed at 1 *G*.
Airspeed depends on trim.

You don't need to worry about load factor except during steep turns and suchlike, so usually you just trim for airspeed. More generally, you trim for angle of attack. Section 2.6 discusses making changes in angle of attack.

Conclusion, valid always:

Trim for angle of attack.

Do not trim for pitch attitude. Do not trim for rate of climb. Trim for airspeed at 1 *G*. Trim for angle of attack!

2.4 Three Contributions to Angle of Attack

As mentioned earlier, it is difficult to directly perceive angle of attack. Fortunately, there are three other quantities that can be perceived, and together they determine the angle of attack. They are:

- Pitch attitude, which is defined[4] to be the angle that the fuselage makes relative to the horizontal.
- Angle of climb, which is just the angle between the flight path and the horizontal.
- Angle of incidence, which is the angle at which the wings are attached to the fuselage.

These quantities are related to the angle of attack by a very simple formula:

Pitch Attitude + Incidence = Angle of Climb + Angle of Attack

This relationship is illustrated in figure 2.2. Perhaps the simplest case is straight and level flight at cruise airspeed. In this case, the pitch attitude is zero, the angle of climb is zero, and the angle of attack is equal to the angle of incidence. Some more examples, with specific numbers for a typical airplane, are included in table 2.1.

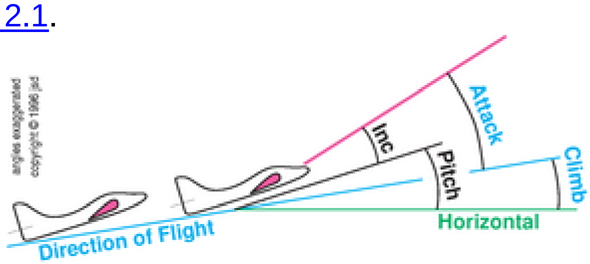


Figure 2.2: Pitch + Incidence = Climb + Attack

Extending the flaps has the effect of increasing the incidence[5] by several degrees. You need to be always aware of what flap setting you are using, and to recognize the distinction between "pitch attitude" and "pitch attitude plus incidence". For any given flap setting, you can take the incidence to be constant, whereupon angle of attack depends only on pitch attitude and direction of flight.

The table mentions V_X and V_Y, which denote the airspeeds for best angle of climb and best rate of climb, respectively, as discussed in section 7.5. The relationship of airspeed to angle of attack will be discussed in section 2.12.

	Airspeed (K_{CAS})	Pitch Attitude	Incidence	Angle of Climb	Angle of Attack
stall	59	14.0	4.5	0	18.5
level at V_X	64	8.5	4.5	0	13.0
level at V_Y	76	4.0	4.5	0	8.5
climbing at V_Y	76	7.0	4.5	3	8.5
cruise	115	0.0	4.5	0	4.5

Table 2.1: Angles in various situations

2.5 Perceiving Pitch Angle

In straight and level flight you can control angle of attack by controlling pitch attitude. You won't be able to pick a particular angle of attack such as 6.37 degrees, but whatever angle of attack you've got can be maintained.[6]

There are at least four ways of perceiving pitch attitude. Perhaps the best way is to use a mark on the windshield, as shown in figure 2.3. The line of sight from your eye through the mark makes a good pointer. (Try not to move your head up and down too much!) If you can't find a scratch or bug-corpse in exactly the right place, you can *make* a mark, or a pair of marks, as discussed in section 11.5.2. It is even simpler to rest your hand atop the instrument panel, holding the tip of your finger in the right place, as shown in figure 11.2.

Suppose you identify (or make) the mark when the airplane is flying at the angle of attack that corresponds to V_Y. Then if you re-trim for a higher angle of attack[7] the sight line through that mark will point two or three degrees above the horizon. Similarly, if you re-trim for high-speed cruise, the sight mark will appear three or four degrees below the horizon.

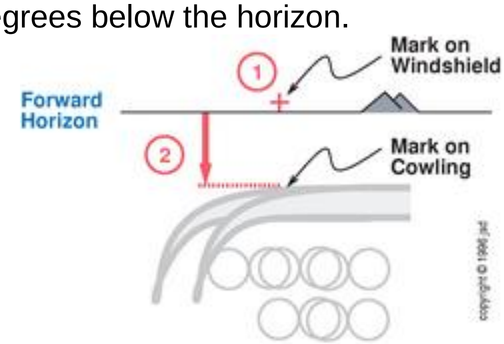


Figure 2.3: Perceiving Pitch Using The Forward Horizon

The second way of perceiving pitch attitude also involves looking out the front, but uses a sight line through a point on the cowling. This is also indicated in figure 2.3. Be sure you chose a point on the cowling directly ahead of your dominant[8] eye; if your seat is way over on one side of the airplane and you choose a sight mark on the middle of the cowling, your sight line will be angled sideways, which will mess up your pitch attitude perception as soon as you try to bank the airplane. A Cessna 152 or 172 has a bolt on the cowling, directly ahead of the pilot, that makes a good sight mark.

A sight mark on the cowling has the advantage that it is farther away from your eye, so it is easier to keep both it and the horizon in focus at the same time. The disadvantage is that the sight line constructed this way sometimes points quite a ways below the horizon. This means the angle you are trying to perceive --- the angle between this reference line and the relative wind --- is larger. It is always harder to perceive a small change in something large than a small change in something that was small to begin with.

Using the cowling has one big advantage over using marks on the windshield: the cowling is a permanent part of the airplane and is in the same place on all airplanes of that make and model.

The third way to perceive pitch attitude is to observe the angle between the wing and the lateral horizon, as shown in figure 2.4. On a high-wing airplane, the bottom surface of the wing makes a good reference. In particular, on a Cessna 152 / 172 / 182, the bottom surface has a rather large flat section, which makes an ideal reference --- and this reference is very nearly aligned with the horizon at cruise angle of attack (in level flight).

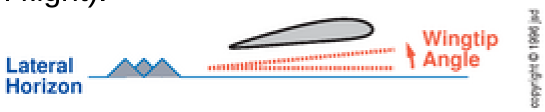


Figure 2.4: Perceiving Pitch Using The Lateral Horizon

On a low-wing airplane, you typically have to use a little more imagination to use the wing as a reference pointer --- but it is definitely possible and definitely worth the effort. Sometimes it helps to envision the chord line with your mind's eye. If you control the angle between the chord line and the lateral horizon, you are controlling pitch attitude.

The idea that you can control pitch attitude while looking out the side window is very important. Aerobatics pilots often attach crosshair-like pointers to their wings, just so they can be sure to have an easy-to-use pitch attitude reference when they're looking out the side. Conversely, it is common to find students who (although they can fly OK while looking out the front) lose control of pitch as soon as they try to look out the side; this makes it tough to check landmarks or scan for traffic.

The fourth way of perceiving pitch attitude is to use the attitude indicator instrument --- the artificial horizon. This has the drawback that it is much too close to your eye; you can't look at the attitude indicator and look for traffic at the same time. You should use outside pitch references whenever possible.

Note: Most of the time, you are primarily concerned with *changes* in the pitch angle. That is, you don't usually need to know that the pitch angle is 1.234 degrees, or any other specific value. If you wanted to really quantify the pitch angle, you would have to decide whether to measure it relative to the wing, relative to the cowling, or relative to a mark on the windshield, et cetera ... but for practical piloting purposes you don't need to quantify it. You just need to perceive changes, and any or all of the aforementioned references will work fine for that.

2.6 Making Changes in Angle of Attack

The push/pull motion of the yoke and the trim wheel are part of the same system, jointly controlling the angle of attack. They also jointly control airspeed, as discussed in section 2.12.

If you want to make a temporary increase in angle of attack, just raise the nose by applying a little back pressure on the yoke. When you reach the new pitch attitude, you can release most of the pressure, and for the first few moments the airplane will maintain the new pitch attitude. Then, as it slows down, you will need to maintain progressively more back pressure in order to maintain the new pitch attitude (and new angle of attack). After a few seconds things will stabilize at a new pitch attitude, a new angle of attack, and a new airspeed. At this point, if you release the back pressure, the airplane will want to drop its nose so it can return to its trimmed angle of attack.

If you push or pull the airplane off its trim speed and then suddenly let go of the yoke, the airplane will not return smoothly and immediately to its trim speed; there will be some phugoid oscillation (as discussed in section 6.1.12).

To undo a temporary change in angle of attack, the proper technique requires observing and controlling the pitch attitude. Let the nose drop to the correct pitch attitude, then apply enough back pressure to keep it from dropping farther. Then, as the airplane gradually returns to its trim speed, you will need progressively less pressure.

Similar logic applies to making long-term changes in angle of attack. Use the yoke to change the pitch attitude. At first very little pressure will be required to maintain the new pitch attitude. Then, as the airspeed changes, use pressure on the yoke to keep the attitude where you want it. Make the change permanent by using the trim wheel to trim off the applied pressure.

Lead with the yoke
then trim off the pressure.

Let's see how these ideas apply to a typical maneuver: levelling off from a climb. Initially let's suppose you start out nicely trimmed, climbing at 475 feet per minute at 90 knots true airspeed.[9] As discussed in section 2.11, that means your direction of flight is 3 degrees above the horizon. As shown in figure 2.5, the first step in the level-off is to change your direction of flight so it becomes horizontal. During the brief time that the direction of flight is changing, the aircraft will be out of equilibrium; lift will be less than weight. The load on the aircraft and its occupants will be slightly less than one *G*.

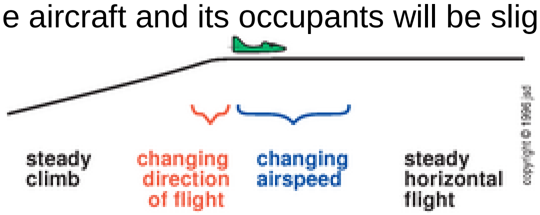


Figure 2.5: Level-Off Maneuver

As the direction of flight changes, you will need to lower the nose the same amount (three degrees). At this point, since the direction of flight and the pitch attitude have changed together, the angle of attack is (for the moment) the same as it was during the climb. This can be seen by comparing the top two parts of figure 2.6. The airspeed is still 90 knots, which is the trim speed, so no yoke force will be needed to maintain the new attitude (for the moment). So far so good.

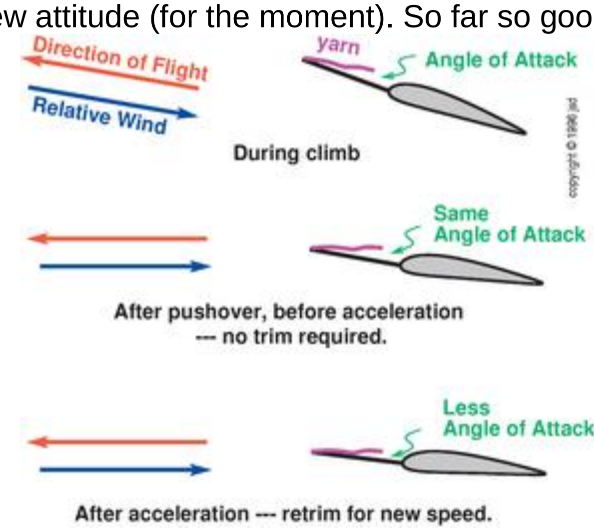


Figure 2.6: Angle of Attack during Level-Off

Since the airplane is no longer climbing, the engine power that had previously been devoted to increasing the altitude is now being devoted to increasing the airspeed. (See section 1.3.1.)

As the airplane gradually accelerates from climb speed to cruise speed, the direction of flight remains horizontal, so the pitch attitude gradually decreases as the angle of attack decreases. This is shown in the bottom part of figure 2.6. You need to apply progressively more forward pressure. In a trainer you might trim off this pressure all at once, but in a high-powered airplane you need to re-trim repeatedly, in stages, as the airplane keeps accelerating and accelerating.

Eventually, the airplane will reach cruise speed. At this point, the airplane has all the altitude (potential energy) and airspeed (kinetic energy) that it needs, so you should throttle back to cruise power. Now[10] you make your final trim adjustment and the level-off maneuver is complete.

Here is a useful trick: make a note of how much trim change is required in your favorite airplane to make the transition from climb to cruise. It is some definite amount, and remembering this amount obviates a lot of guessing and fiddling.
I remember the amounts in terms of “sectors” and “bumps”. That is, on most airplanes only a certain sector of the trim wheel is exposed, and this defines how much trim change can be achieved with a single hand motion; I call this one sector. Similarly, the trim wheel typically features a series of bumps, to make it easier to grasp. Each bump represents 1/4th or 1/5th of a sector.
Suppose after cruising in level flight for a while, you decide to climb to a higher altitude. If you roll in three sectors of nose-up trim as you start the climb, you can bet that you will need roll those three sectors back out to return to cruise airspeed afterwards. Maybe the right answer won’t be *exactly* three sectors, because your indicated airspeed at the new cruise altitude may be slightly different. But having some idea is better than having no idea! Apply the expected amount of trim, see how it works, and then trim off any slight yoke force that remains.

Similarly, suppose you are cruising along and encounter an updraft. If you roll in half a bump of nose-down trim to help you maintain altitude, you can bet that you will need to roll that half-bump back out when you exit the updraft and return to normal airspeed. Keep track of the amount! Say to yourself, “I’m carrying a half-bump of nose-down trim which I’ll have to get rid of sooner or later”.

2.7 Fly with a Light Touch

Here’s some really important advice: You should at all times be aware of how much force you are putting on the yoke. You don’t want to accidentally pull the airplane off its trim speed.

Usually this is summarized by saying “keep it trimmed, and fly with a light touch”, but “light touch” is a relative concept, and somewhat hard to quantify:

> Some airplanes have such heavy control forces that it’s difficult to imagine anyone accidentally pulling the airplane off its trim speed. You need to trim it properly lest you wear yourself out trying to hold the yoke.

> Many planes have such light control forces that if you keep a tight grip on the yoke, you could easily pull the airplane ten knots away from its trim speed without feeling it.

In all cases, the important thing is to be *aware* of how much force you're putting on the yoke.

I once flew with a pilot who held the yoke so tightly that his knuckles turned white, literally. Every time he looked to the right, the airplane pitched down 10 or 15 degrees. Every time he looked to the left, the airplane pitched up 10 or 15 degrees. It's a good thing he didn't look to the left very long; otherwise we might have stalled.

For almost any plane, from C-152 to Airbus, if you trim it properly you will be able to fly most maneuvers using just your thumb and one or two fingertips.

There are some exceptions; for instance the B-24 was notorious for its heavy control forces. But that just makes trimming even more important.

There are of course some maneuvers, notably the landing flare, where everything is changing so quickly that it's not worth re-trimming, and goodly amounts of force may be needed.

The yoke is not just a control carrying commands from you to the airplane --- it is also a valuable sensor carrying information from the airplane to you. This is discussed in more detail in section 12.12.

You should make sure the airplane is at all times trimmed for the right airspeed (or, rather, angle of attack). You should be aware of (and wary of) any force you apply to the yoke, forcing the airplane off its trim speed.

Fly with a light touch!

2.8 Trim Won't Solve All The World's Problems

Although the airplane's tendency to return to its trimmed angle of attack is very powerful, very important, and usually very helpful, there is more to the story.

If the airplane is disturbed from its trimmed angle of attack, it will not just return; it will overshoot. It will oscillate a few times before settling down. These phugoid oscillations are slow enough that you can easily extinguish them by timely pressure on the yoke, as discussed in section 6.1.12.

In smooth air, you can trim the airplane and let it fly itself. However, turbulent air will frequently provoke new phugoid oscillations so you will frequently need to apply small nudges to the yoke.

For similar reasons, it is not normal procedure to use the trim wheel to *initiate* a change in pitch attitude, airspeed, or angle of attack. That would just provoke an oscillation. Initiate the change with the yoke as described above. Put the pitch attitude where it belongs, keep it there with the yoke, and then trim off the pressure.

Finally, in some airplanes the trim speed is perturbed when you add power, when you extend flaps, and especially when you have power and flaps at the same time. See section 5.5 and section 12.10.

2.9 Pitch Attitude versus Angle of Attack

The previous sections pointed out that while pitch attitude and angle of attack are related, they are not quite the same. Pitch attitude is measured relative to the horizon, but angle of attack involves the direction of the relative wind. In any situation where the relative wind is not horizontal, we have to be careful.

I forgot the distinction once; let me tell you the story. One summer I spent several weeks at the Aspen Center for Physics. This was my first opportunity to do any mountain flying, so I arranged for a lesson from the flight school at Aspen. The lesson included flying over the continental divide and landing at Leadville. Leadville is famous for being the highest airport in the United States --- 9900 feet above sea level. On the day in question, it was about 90°F in the shade, so the density altitude at Leadville was around 13,000 feet, and I knew takeoff performance would be critical.
I used my best short-field procedure, even though the runway was 5000 feet long. I accelerated on the runway to the proper climb-out speed (75 knots indicated, 90 knots true) and then rotated to what I assumed was the correct climb-out attitude. Based on my experience at lowland airports, I knew that 11 degrees of nose-up attitude was usually just right for climb out. Following my usual habit, I scanned the airspeed indicator after we had climbed a few feet. To my horror, I observed that the airspeed was decreasing rapidly. I immediately lowered the nose, and flew the airplane in ground effect while it regained speed. (What had been intended as a short-field procedure ended with a peculiar imitation of soft-field procedure.) I used up almost the entire runway getting back to 75 knots. At 75 knots I rotated again, choosing a much lower pitch attitude this time. We climbed out at 75 K_{IAS} and the rest of the lesson was relatively uneventful.

Figure 2.7 shows the normal takeoff procedure at a low-altitude airport. Figure 2.8 shows that using the normal pitch attitude does not produce the normal angle of attack at a high-altitude airport, because the angle of climb is an indispensable part of the equation. Figure 2.9 shows how to do it right. Table 2.2 summarizes the arithmetic.

Figure 2.7: Climbing Out From Lowland International

Figure 2.8: Climbing Out From Leadville (Wrong)

Figure 2.9: Climbing Out From Leadville (Right)

Understanding what went wrong in this scenario is very instructive. The main difference between a sea-level takeoff and a mountain takeoff is that the airplane does not climb nearly so steeply. The direction of flight is much more nearly horizontal. As can be seen by comparing figure 2.8 with figure 2.9, this means a much lower pitch attitude is needed to achieve the same angle of attack.

The really embarrassing part of my story is that I had actually calculated the climb gradient as part of my preflight preparation, to make sure I could clear obstructions. I just didn't make the connection between the climb gradient (which I calculated) the best-climb angle of attack (which I knew) and the pitch attitude (which I used for controlling the airplane). Fortunately I did know the connection between airspeed and angle of attack, and I scanned the airspeed indicator before the situation got too far out of hand.

	Calib. Airspeed	Pitch Attitude	Incidence	Climb Rate @ True Airspeed	Angle of Climb	Angle of Attack
sea level	76 K_{CAS}	11.0	4.5	900 fpm @ 76 K_{TAS}	7	8.5
Leadville (wrong)	dropping rapidly	11.0	4.5	200 fpm @ 90 K_{TAS}	1	14.5
Leadville (right)	76 K_{CAS}	5.0	4.5	200 fpm @ 90 K_{TAS}	1	8.5

Table 2.2: Right versus wrong climb attitude

2.10 Power plus Attitude does not equal Performance

You may have heard the assertion that “Power plus Attitude equals Performance”. Well, that assertion is not quite right, and has caused all sorts of unnecessary confusion.

Consider the following scenario: You are cruising along in a typical 180 horsepower, one-ton aircraft. You have constant power and constant attitude, so you expect constant performance. You do indeed get constant performance, and everything seems just fine.

Now, just raise the nose to a 15 degree nose-up attitude, and hold that attitude as accurately as you can. You will once again have constant power and constant attitude, so you might expect constant performance --- but that is definitely not what you will get. Instead, you will get decreasing airspeed and increasing angle of attack. The initial climb that looked so promising will peter out and you will wind up on the edge of a stall.

If you think about this situation in terms of *energy* and *angle of attack*, the airplane’s behavior is completely predictable.

First of all, we need to remember that not all climbs are steady climbs. As portrayed in figure 2.10, it is possible for a roller-coaster with no engine at all to zoom up a little ways by cashing in its initial kinetic energy. Just because it starts out on a certain climb trajectory doesn’t mean it can continue.

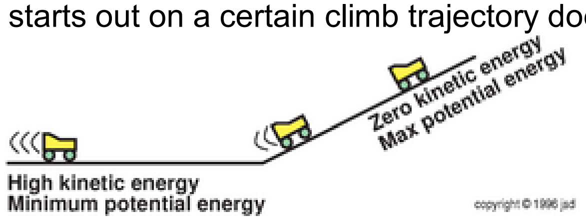


Figure 2.10: Climb Powered by Speed

Airplanes, too, can be placed on climb trajectories that cannot be sustained by the available engine power. The initial climb succeeds only because airspeed is being cashed in to purchase altitude.

Unlike a roller-coaster, the airplane will not stay on its initial trajectory until it runs out of speed altogether. As the airspeed decays, the airplane will have to fly at a higher angle of attack in order to support its weight. Since, as discussed above, the angle of attack depends on the angle between the pitch attitude and the direction of flight, a constant attitude implies a non-constant direction of flight, as indicated in figure 2.11.

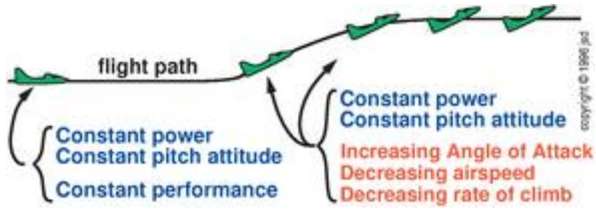


Figure 2.11: Constant Power & Attitude but Changing Performance

If you are lucky, the changing flight path will result in a trajectory where the rate of climb and the drag budget can be sustained by engine power, with no further decrease of airspeed; otherwise the maneuver will end in a stall.

One of the maneuvers you have to perform in order to get a commercial pilot certificate is called a *chandelle*. As discussed in section 16.14, it involves turning as well as climbing, but if you disregard the turning part, the maneuver is exactly what is portrayed in figure 2.11. This maneuver is an important part of the syllabus because it forces people to learn that constant power and constant attitude do not imply constant performance.

As discussed in section 2.6, a pitch attitude excursion is not necessarily the same as an angle of attack excursion. Suppose due to turbulence or whatever, the pitch attitude and direction of flight both increase by 15 degrees. If you correct the situation promptly, the airspeed and altitude will not have time to change much. If on the other hand you allow the pitch excursion to persist, the airplane will begin to follow the chandelle trajectory shown in figure 2.11. The altitude will increase (at least at first), the airspeed will decrease, and the angle of attack will increase. It is good pilot technique to correct pitch attitude excursions before they turn into altitude / airspeed / angle of attack excursions.

To summarize: the Leadville scenario and the chandelle scenario prove that angle of attack is far more important than pitch attitude in determining performance. But this does not mean you disregard pitch attitude --- far from it. I recommend that you use pitch attitude as a *means* of controlling angle of attack --- just don’t use pitch attitude as a *substitute* for controlling angle of attack.

2.11 Estimating the Relative Wind

As discussed above, to control the angle of attack you need to know both the pitch attitude and the direction of flight.[11] I have given several methods for estimating the pitch attitude. Now it is time to explain how to estimate the direction of the relative wind. This is almost the same thing as estimating direction of flight.

In level flight, the task is easy: The relative wind is coming at you horizontally. (Again, I am assuming there are no major updrafts or downdrafts.)

If the airplane is climbing or descending, the origin of the relative wind will be above or below the horizon, respectively. The amount above or below depends on the ratio of your vertical speed to your airspeed. I have committed some of the numbers to memory; for instance, I know that flying a standard 3 degree glideslope at 90 knots involves a 480 fpm descent. Using the same little fact in reverse tells me that if I am climbing out at 90 knots and the vertical speed indicator (VSI) is reporting 480 fpm, I must be flying toward a point 3 degrees above the horizon; to say it the other way, the relative wind must be coming toward me from that point, three degrees above the horizon. That means that I can relabel the VSI as a “direction of flight” indicator, as shown in figure 2.12. Any particular relabeling is only valid for one airspeed.[12]

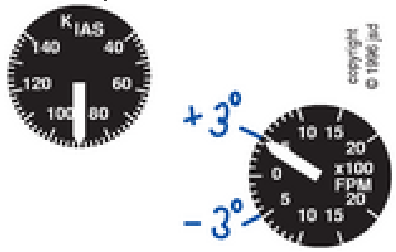


Figure 2.12: Vertical, Horizontal Speed Gauges Determine Angle

If you maintain 90 knots and transition from level flight to a 480 fpm climb, you will have to raise the pitch attitude 3 degrees in order to maintain the same angle of attack.[13]

If you want to know the vertical speed that corresponds to some other angle and/or some other horizontal speed, you can refer to table 2.3; a similar table appears in every “instrument approach procedures” booklet published by the US government. The inverse table (finding the angle, given horizontal and vertical speeds) is shown in table 2.4.

		Horizontal speed / knots				
		60	75	90	105	120
Angle	3°	320	400	480	555	635
	4°	425	530	635	745	850
	5°	530	665	795	930	1065
	6°	640	800	960	1120	1275
	7°	745	935	1120	1305	1490
	8°	855	1065	1280	1495	1710

Table 2.3: Vertical Speed vs. Angle and Horizontal Speed

		Horizontal speed / knots				
		60	75	90	105	120
Vertical Speed fpm	250	2.4	1.9	1.6	1.3	1.2
	500	4.7	3.8	3.1	2.7	2.4
	750	7.0	5.6	4.7	4.0	3.5
	1000	9.3	7.5	6.3	5.4	4.7

Table 2.4: Angle vs. Vertical Speed and Horizontal Speed

The VSI is not the only way of determining the direction of flight. If you are established on an ILS approach, as long as the glideslope needle stays centered you are descending at a known angle (usually three degrees). Similarly, there might be a VASI or other approach slope indicator that you could follow. As always, it is better to use outside references instead of instruments.

Perhaps the best way to judge the angle of descent is to use the “rule of thumb” as discussed in section 12.3. That frees you from relying on any fancy equipment.

If you control the direction of flight using any of these techniques, and control the pitch attitude using the techniques discussed elsewhere in this chapter, then you are also controlling the angle of attack.

Actually, there is one more ingredient in this recipe: the wind. Three of the methods just mentioned (VASI, electronic glideslope, and rule of thumb) give you information about your direction of flight relative to the ground, but the angle of attack depends on your direction of flight *through the air*. In the presence of wind, the two are not quite the same. This is discussed in section 12.4.3. The scheme of estimating the direction of flight using the VSI gives the correct answer even when nature's wind is blowing (provided, again, there are no major updrafts or downdrafts).

Outside references should be your primary means of controlling angle of attack. Every so often you should look at the airspeed indicator to make sure you have got the *right* angle of attack (as discussed in section 2.12), but you should maintain that angle of attack by outside references.

Suggestion:

- One look out of ten, look at the instruments.
- Nine looks out of ten, look at the outside references.

2.12 Airspeed Is Related to Angle of Attack

2.12.1 Airspeed versus Coefficient of Lift

So far in this chapter I have mentioned that the critical performance numbers usually specified by airspeeds such as V_Y are really angle of attack recommendations.

Specifically:

- I have mentioned that the trim wheel really controls angle of attack but to a good approximation controls airspeed.
- I have mentioned that the airspeed indicator saved my bacon when I had an angle of attack problem at Leadville.

Therefore you are probably beginning to suspect that there might be a relationship between angle of attack and airspeed. That's right! The purpose of this section is to tell you why you can use the airspeed indicator to control angle of attack, when you have to compensate for its imperfections, and when you can't trust it at all.

The basic line of reasoning is this: the amount of lift produced by the wing depends on angle of attack and calibrated airspeed. We can turn this around to get a simple relationship between airspeed and angle of attack (assuming lift is known, as it usually is). The key formula is

$$\text{lift} = \tfrac{1}{2}\rho V^2 \times \text{coefficient of lift} \times \text{area} \qquad (2.1)$$

The coefficient of lift will be discussed below, and (in more detail) in section 4.5. The quantity $\frac{1}{2}\rho V^2$ is called the *dynamic pressure*, also called *Q* for short, but more often than not people just call it one-half rho vee squared.

The quantity $\frac{1}{2}\rho V^2$ is tremendously important, as discussed in section 2.12.3.

You don't need to calculate $\frac{1}{2}\rho V^2$ because your airspeed indicator does it for you. You may have thought that an airspeed indicator would ideally measure the *true airspeed* (which is simply the genuine speed of the air relative to the aircraft, denoted *V* in all the formulas). However, the airspeed indicator doesn't even try to measure V (i.e. the square root of V^2); instead it tries to measure something called *calibrated airspeed* (CAS), which is proportional to the square root of $½\rho V^2$. Note the factor of ρ in the CAS formula.[14] While we're on the subject, *indicated airspeed* (IAS) refers to whatever is indicated on your airspeed indicator. It is the same as calibrated airspeed, plus whatever errors there are in the mechanism. This discussion assumes that your instrument is not too wildly inaccurate, so that formulas that apply to CAS exactly also apply to IAS accurately enough for present purposes.[15]

In flight, the lift is nearly always equal to the weight times load factor.[16] The weight is presumably not changing much from moment to moment. This leads us to rearrange the lift equation as follows:

$$\text{coefficient of lift} = (\text{weight} \times \text{load factor}) / (½\rho V^2 \times \text{area}) \qquad (2.2)$$

If the airspeed goes down, the coefficient of lift must go up. This relationship is illustrated in figure 2.13.

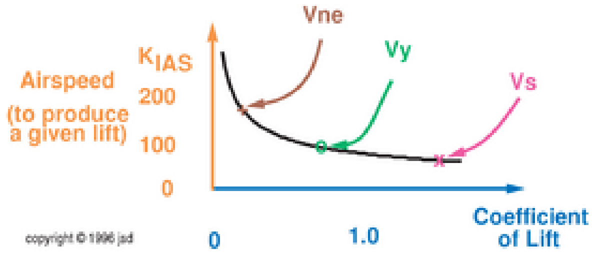


Figure 2.13: Airspeed versus Coefficient of Lift

Three of the critical V-numbers are marked in figure 2.13; each corresponds to a particular coefficient of lift.

2.12.2 Coefficient of Lift versus Angle of Attack

Now we bring in a new fact: The coefficient of lift is a simple function of the angle of attack. This dependence is shown in figure 2.14. Note that for small angles of attack, the coefficient of lift is essentially proportional to the angle of attack. The angle of attack that gives the maximum coefficient of lift is called the "critical angle of attack" and is marked in the figure.

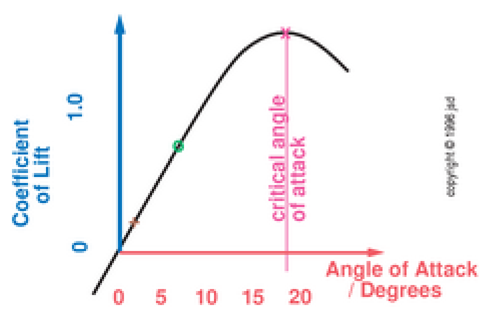


Figure 2.14: Coefficient of Lift versus Angle of Attack

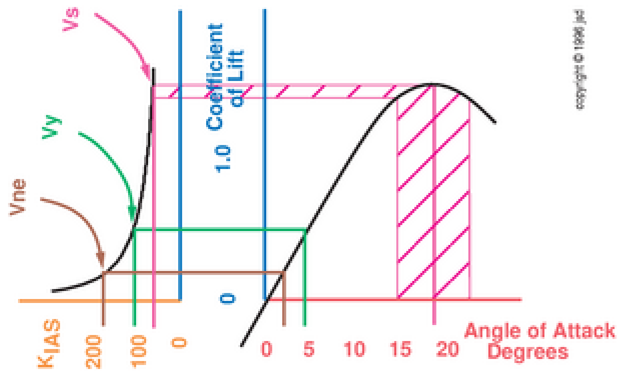


Figure 2.15: Airspeed Is Related to Angle of Attack

By combining this fact with what we already know, we can establish the relationship between angle of attack and indicated airspeed. We combine figure 2.13 with figure 2.14, as is done in figure 2.15. We see that a particular *V*-number, such as V_{NE}, corresponds to a particular coefficient of lift, which in turn corresponds to a certain angle of attack. The same goes for most of the other *V*-numbers, such as V_Y. The argument works in reverse, too: any particular angle of attack corresponds to a particular airspeed (assuming we know how much lift is being produced).

We conclude that the airspeed indicator is really a pretty good angle of attack indicator --- with one major exception: There is a whole range of angles of attack near the critical angle of attack that all produce about the same coefficient of lift (because the coefficient of lift versus angle of attack curve is quite flat on top). All the coefficient-of-lift values in this small range correspond to nearly the same airspeed --- namely V_S, the stalling airspeed.

The stall is a very critical flight regime. This is a regime where you would very much like to have an accurate instrument to indicate angle of attack, and alas it is the one regime where the airspeed indicator doesn't tell you anything you need to know.

You want to land the airplane at a very high angle of attack. You will have to perceive the angle of attack using outside visual cues, as discussed in the previous sections. During the flare, the airspeed indicator doesn't tell you anything you need to know. I once asked an airline captain to tell me at what airspeed his airliner touched down. He said "I don't know; I never looked. I've always had more important things to look at". That was a good pilot's honest answer.

2.12.3 Correcting for Reduced Density

In all non-stalling regimes of flight, including (especially) final approach, the airspeed indicator provides your most quantitative information about angle of attack. We now discuss some corrections that may be needed.

The airspeed indicator is basically a pressure gauge; the pressure that moves the airspeed needle is the same dynamic pressure that holds up the wings in accordance with the lift formula (equation 2.1). Knowing the pressure that holds up the wing is more important than knowing your true airspeed.

The airspeed indicator is doing you a favor by not measuring speed *per se*. It is telling you what you most need to know. Remember that calibrated airspeed is what holds up your wings. In principle, the calibrated airspeed depends on true airspeed and on density, and the density depends on altitude, temperature, and humidity ... but the wing doesn't care about any of those details; it only cares about the calibrated airspeed in accordance with equation 2.1. For instance, on final approach you should fly the proper indicated airspeed. At high density altitudes this will be a higher-than-normal true airspeed.

In other words: do not correct V_Y, V_S, glide speed, or approach speed (1.3 V_{S0}) for altitude or temperature. Trust the calibrated airspeed. These speeds need to be corrected for weight (section 2.12.4) but not for density altitude.

The true airspeed that corresponds to any given calibrated airspeed will be higher, by about 2% per thousand feet of density altitude. Your groundspeed will also be greater.

When landing at a high-altitude airport, the greater groundspeed means you will need more runway length, by about 4% per thousand feet of density altitude. Check the charts in your POH.

A high-altitude takeoff is even worse than the landing, because the engine (unless turbocharged) will be producing less power. Check the charts in your POH. Apply a generous safety factor, since many of the handbooks are disgracefully overoptimistic. Do the takeoff planning (not just the landing planning) before you land, lest you go into an airport you can't get out of.

2.12.4 Correcting for Reduced Lift Requirements

So far we have been assuming the weight was equal to some standard value. Let's relax that assumption and see what happens.

It is easy to imagine flying a Cherokee Six at half of its maximum legal weight. (See section 7.5.8 for more on this.)

The problem is that the Pilot's Operating Handbook for the airplane specifies all the critical angle of attack information in terms of speeds --- speeds that only apply at max weight. We know that the airplane stalls at a definite angle of attack, not at a definite airspeed or anything else.

In general, if you keep the angle of attack constant and lower the weight of the airplane by 10%, the airspeed needed to support that weight goes down by 5%. This is because the lift depends on the *square* of the airspeed in equation 2.1; the square root of 0.90 is 0.95 and the square root of 1.10 is 1.05. For really large changes in weight, the speed change is even somewhat greater; the square root of 0.50 is not 0.75 but rather 0.707.

At reduced weights approach speed and best-glide speed must be reduced below their standard-weight handbook values, according to the square root of the weight. The V_X and V_Y values should be reduced by approximately the same factor. The maneuvering speed must also be reduced, although for different reasons, as discussed in section 2.13.2.

> The percentage change in speed
> is half of the percentage change in weight.

Since the cruise speed depends mainly on power and parasite drag, it hardly depends on angle of attack. That means it does *not* decrease as the weight is decreased; the situation is depicted in figure 7.13 in section 7.5.8. Also, in a multi-engine airplane, V_{MC} may or may not depend on lift requirements, so the safest thing is to not reduce it.

2.12.5 Correcting for Increased Lift Requirements

There is one fairly common situation where maintaining a given angle of attack requires flying at airspeeds *above* the *V*-numbers given in the Pilot's Operating Handbook.

In a steep turn, the wings are required to produce enough lift not only to support the airplane's weight, but also to shove it around the corner. In a 60 degree bank, the lift requirement is doubled. We say there is a load factor of 2.0. The airspeed necessary to produce this lift at a given angle of attack is increased by a factor of √2, which is 1.41.

If you are going to use the airspeed indicator as a source of angle of attack information, you have to take this into account. If you fly at a speed near the bottom of the green arc in a steep turn, the airplane will stall. For example, if the airplane stalls at 60 knots in unaccelerated flight, it will stall at 85 knots in a 60 degree banked turn (since 60 × 1.41 = 85).

Also remember that the airplane is trimmed for a definite angle of attack, and it really wants to maintain that angle of attack. If you are cruising along, trimmed for 120 knots in straight and level flight, and the airplane gets into a 60 degree bank, it will accelerate to 169 knots (120 times the square root of 2) in order to meet the increased lift requirement at the same angle of attack. This situation is described in more detail in section 6.2.

2.12.6 Compute with Calibrated not Indicated Airspeed

In a wide range of airplanes, it turns out that a good airspeed for final approach is 1.3 times the stalling speed.[17]

When applying this rule, a little sophistication is necessary, or you might get into trouble. In particular, you must not just look at the indicated stalling speed on the airspeed indicator, multiply by 1.3, and then try to use the result as your indicated airspeed on final.

The only safe way to calculate the approach speed is to multiply the *calibrated* stalling speed by 1.3, and then convert the result an indicated airspeed. That is, if you know the indicated stalling speed, the correct procedure is:

a) convert the indicated speed to a calibrated speed, using the conversion information in the Pilot's Operating Handbook;

b) multiply the calibrated speed by 1.3; and

c) convert this calibrated approach speed back to an indicated airspeed you can use in the cockpit.

Table 2.5 shows an example which contrasts the right and wrong calculations.

	CAS	IAS	safe approach speed?
stall	50	43	
1.3 × indicated stall	58	56	no
1.3 × calibrated stall	65	65	yes

Table 2.5: Calibrated versus Indicated Approach Speed

The origin of the problem is this: It is possible to position the Pitot tube and static port so that the IAS is a few knots higher than the CAS in cruise conditions, yet a few knots lower than the CAS near the stall. Manufacturers commonly do this, presumably in hopes of making pilots think the airplane performs better than it really does. (In contrast, you will probably never see an instrument that underestimates the top speed or overestimates the stalling speed.)

These errors would not be much of a problem if the the IAS were simply proportional to the CAS. The constant of proportionality would drop out of the calculation, and you could skip steps (a) and (c). Alas, in many airplanes the errors are highly nonlinear. The indicated airspeeds are much too low at the low end of the scale. If you multiply such a low number by 1.3, you get a number that is still much too low, but falls at a place where the gauge is more accurate, so you wind up with a real airspeed that is dangerously low.

You may we wondering about other calculations, such as the corrections for nonstandard weight. Should calculations also be done using calibrated airspeed? The answer, alas, is not 100% obvious. It depends on whether you think the errors in the system depend on airspeed itself, or depend on angle of attack.

- In the rather unlikely case that the error is in the gauge itself, it would be better to convert to CAS, multiply, and convert back to IAS.
- More often, the airspeed instrument itself is a very accurate pressure gauge, but the Pitot and static ports are positioned so that they pick up bogus pressures at high angles of attack. In such a case you should calculate the weight-correction using indicated airspeed directly. That is, if you are at 64% of standard weight, your indicated airspeed should be 80% of the standard indicated airspeed. The point is that you want to fly the maneuver at the correct angle of attack. If the errors depend only on angle of attack, they drop out of this calculation.

You might want to measure your airplane, as follows: Fly it at its maximum weight, at a safe altitude, and observe the indicated airspeed at which the stall warning horn comes on. Do this in the clean configuration[18] and in the landing configuration. Then repeat the measurements at the lowest convenient weight. Then you will know for sure how the indicated airspeed varies with weight, at particular angles of attack.

2.12.7 Correcting for Slip

It is easy to get into situations where the indicated airspeed is wildly inaccurate. In some airplanes the opening that is supposed to measure the static pressure is located on the side of the fuselage, and during a slip that point is subject to some dynamic pressure in addition to the static pressure.[19]

In such a case you must remember that it is angle of attack that really matters. You can use the airspeed indicator if you wish *before* the slip to help figure out what angle of attack you want, but *during* the slip you must maintain that angle of attack by looking at the angles themselves (pitch angle and direction of flight). See section 11.2 for more on this.

2.12.8 Drag and Lift-to-Drag Ratio

Let’s return to the scenario of the airplane flying at half of its standard weight, and ask (a) what is the best glide speed, and (b) how well will it glide at that speed.

To answer these questions we need to think about drag as well as lift. (Section 2.12.4 concentrated on topics like V_S and V_A which depend on total lift, not lift-to-drag ratio.) Fortunately, the answer comes out the same. This is because the formula for drag,

$$\text{drag} = ½\rho V^2 \times \text{coefficient of drag} \times \text{area} \qquad (2.3)$$

has the same form as the famous formula for lift:

$$\text{lift} = ½\rho V^2 \times \text{coefficient of lift} \times \text{area} \qquad (2.4)$$

The key idea is that the coefficient of drag depends on angle of attack; at any particular angle of attack the coefficient does not perceptibly depend on weight or airspeed. The same is true of the coefficient of lift and the lift-to-drag ratio.

If you want to glide from point *A* to point *B* in no-wind conditions,[20] the main thing you care about is lift-to-drag ratio. For example, if your airplane is capable of a 10-to-1 lift-to-drag ratio, then you can glide to a point that is 1/10th of a radian (i.e. six degrees) below the horizon.

The optimal lift-to-drag ratio is achieved at a definite angle of attack. To support the weight of the airplane at that angle of attack, you will need to fly at a speed proportional to the square root of the weight, for the reasons given in section 2.12.4.

The lightly-loaded gliding airplane will have the same angle of descent, the same direction of flight, and the same total gliding distance, as indicated in figure 2.16. The only difference is that it will have a slower descent rate and a slower forward speed; this is indicated in the figure by stopwatches that show how long it takes the plane to reach a particular point.

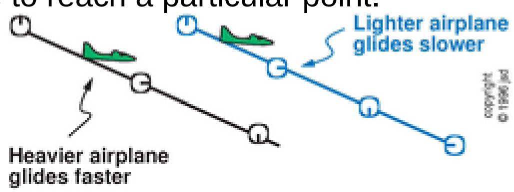


Figure 2.16: Angle of Glide Independent of Weight

The moral of the story is if you are flying a lightly-loaded airplane, you should fly it “by the numbers”, namely the angle of attack numbers. The critical airspeed numbers (climb speed, approach speed, stalling speed, etc.) are all reduced according to half the weight-change percentage. That is, if you are 10% light, reduce the handbook speeds by 5%.

There is one well-known exception to the rule of thumb that says important performance speeds decrease as the weight decreases. That is, the cruising speed actually increases at reduced weights. This is not an exception to the real rule that speeds should vary with weight *at a given angle of attack,* because cruising speed is not tied to a particular angle of attack. If the airplane is lightly loaded, you can cruise at a lower angle of attack and a higher airspeed, since the wings need to do less work to support the weight of airplane.

2.13 Not Everything Depends on Angle of Attack

Some of the airplane’s critical performance numbers depend directly on angle of attack, while others don’t. It’s somewhat useful to know which are which, so you can know which ones change with the weight of the airplane and which ones don’t.

2.13.1 Explicit Airspeed Limits

There is a *normal-operations* airspeed, V_{NO}. This is indicated by the top of the green arc on the airspeed indicator. You should not exceed this speed except in smooth air, and then only with caution. The idea here is that you don't want to break the wing. There is a maximum coefficient of lift, and the lift force depends on this coefficient times calibrated airspeed squared. By limiting the airspeed, you limit the maximum force that the wing can produce. This is typically what determines V_{NO}.

There is also a *never-exceed* airspeed, V_{NE}. This is indicated by the top of the yellow arc, and by a red radial line on the airspeed indicator. As the name suggests, you should never exceed this speed under any circumstances. This limit depends on many things, including drag force on the primary structure (wings, tail, landing gear etc.); drag force on secondary items (antennas, fairings, etc.); instability of the structure and control systems due to flutter; and other nasty complications.

2.13.2 Maneuvering Speed

If you are flying in moderate or severe turbulence, you should keep your airspeed below the *maneuvering speed*, V_A. By the same token, you should avoid large, sudden deflections of the controls unless your airspeed is below V_A. The idea behind V_A is that you want the wing to *stall* before anything *breaks*. You may think that a stall is bad, but remember that you can recover from a stall much more easily than you can recover from a broken airplane.

> Maneuvering speed means the wing is supposed to stall before it produces enough *G*s to break any part of the airplane.

We say it is *supposed* to stall, not guaranteed to stall, because the formal definition of V_A takes into account only certain types of rough control usage, and only certain types of turbulence (namely purely vertical updrafts and downdrafts). In real life, other possibilities must be considered. For instance, if you start out at V_A and encounter a large horizontal wind shear, arbitrarily large forces can be developed. For this and several other reasons, the exact value of V_A should not be taken too literally.

Still, the general idea of V_A makes sense: If you observe or anticipate a situation that imposes large *G* loads on the airplane, you should slow down and/or confine yourself to gentler maneuvers.

Unlike V_{NO}, the maneuvering speed varies in proportion to the square root of the mass of the airplane. The reason for this is a bit tricky. The trick is that V_A is not a force limit but rather an *acceleration* limit. When the manufacturers determine a value for V_A, they are not worried about breaking the wing, but are worried about breaking *other* important parts of the airplane, such as the engine mounts. These items don't directly care how much force the wing is producing; they just care about the acceleration they are undergoing.

By increasing the mass of the airplane, you decrease the overall acceleration that results from any overall force. (Of course, if you increase the mass of cargo, it increases the stress on the cargo-compartment floor --- but it decreases the stress on unrelated components such as engine mounts, because the acceleration is less.)

This means you should put V_A along with V_S and V_Y etc. on your list of critical airspeeds that vary in proportion to the square root of the mass of the airplane. However, V_A depends on real *mass* not on weight, so unlike the others it does *not* increase with load factor.

To illustrate this point, consider what happens when the airplane is in a steep turn. Compared to unaccelerated flight:

The stalling speed increases (because the stalling angle of attack stays the same), and the airspeed for best rate of climb increases (because the optimum angle of attack stays the same), but

the maneuvering speed remains the same (since it doesn't directly depend on angle of attack).

Finally, we should note that there are two different concepts that, loosely speaking, are called maneuvering speeds.

- The *design* maneuvering speed, which we can denote $V_{A(D)}$, is primarily of interest to aircraft designers, not pilots. The designer must choose a value for $V_{A(D)}$ and then build an aircraft strong enough to withstand certain stressful maneuvers at that speed. Higher values of $V_{A(D)}$ promote safety, by forcing the design to be stronger.
- The maneuvering speed *limitation*, which we can denote $V_{A(L)}$, is of interest to pilots. It is an operating limitation. It appears on a placard in the cockpit. Lower values of $V_{A(L)}$ promote safety, by restricting certain operations to lower, less-stressful airspeeds.

This is a book for pilots, not designers, so when we use V_A it always means $V_{A(L)}$. But you should be careful when reading the FARs and other books, because they sometimes use the same symbol to mean two different things, which makes it very hard to think clearly.

2.13.3 Overview of Limits and Performance Numbers

We see that there are four main classes of numbers:

- The low-speed limits and most of the "optimum" numbers (including the stall, best rate of climb, best lift/drag ratio, best endurance, normal approach, short field approach, etc.) involve, to an excellent approximation, definite angles of attack. The corresponding airspeeds vary in proportion to the square root of weight. (To a second approximation each of these angles of attack will change slightly because of propwash over the wings, propeller efficiency, and other factors that depend on speed and power.)
- The high-speed limits (including never-exceed speed, the normal-operations limit, the landing-gear operation limit etc.) are, for all practical purposes, definite indicated airspeeds.
- The maneuvering limit is not exactly a definite speed (since the limiting speed varies in proportion to the square root of mass) but it is not exactly a definite angle of attack either (since V_A does not depend on load factor in a steep turn).
- Top speed and normal cruise speed depend on weight and engine power, as discussed in section 7.6.5. They also depend on density altitude, as discussed in section 7.5.5. Best angle of climb depends on weight, power, and wind, as discussed in section 7.5.4.

2.14 Absolute versus Geometric Angle of Attack

You can skip this section unless you are trying to compare this book with another book that uses a different definition of "the" angle of attack.

As mentioned in connection with figure 2.1, we are free to choose how the angle-of-attack reference stick is aligned relative to the rest of the wing. Throughout this book, we choose to align the reference with the zero-lift direction. That means that zero angle of attack corresponds to zero coefficient of lift. According to the standard terminology, the angle measured in this way is called the *absolute* angle of attack.

Some other books try to align the reference with the chord line[21] of the wing. The angle measured in this way is called the *geometric* angle of attack.

If you try to compare books, there is potential for confusion, because this book uses “angle of attack” as shorthand for absolute angle of attack, while some other books use the same words as shorthand for other things, commonly geometric angle of attack. To make sense when comparing books, you must avoid shorthand and use the fully explicit terms. The relationship between the two ideas is shown in figure 2.17.

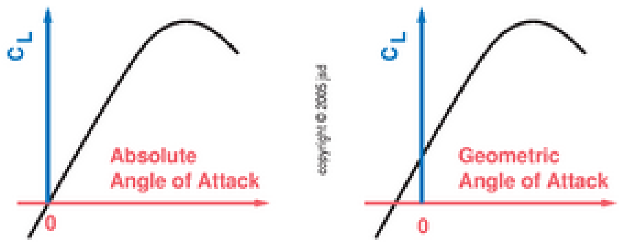


Figure 2.17: Absolute versus Geometric Angle of Attack

Quantitatively, to convert from one system to another:

$$\begin{aligned} \text{absolute angle of attack} &= \text{geometric angle of attack} + k \\ \text{geometric angle of attack} &= \text{absolute angle of attack} - k \end{aligned} \qquad (2.5)$$

where $-k$ is the X-intercept of the graph of the coefficient of lift according to the “geometric” scheme.

In this book, we always use the absolute scheme, so the X-intercept is always zero.

Also note that are many possibilities, not just absolute versus geometric; the choice of reference is really quite arbitrary. It is perfectly valid to measure angles relative any reference you choose, provided you are consistent about it. (Aligning the reference stick with the *fuselage* is useful in some situations; see section 5.5.3.)

Using the chord as a reference works OK if you are only talking about one *section* of a *plain* wing. On the other hand:

- On typical airplanes, the chord of the wing tip is oriented differently from the chord of the wing root. Which one should be considered “the” reference?
- When you extend the flaps, the chord line changes. (See section 5.4.3 and section 5.5 for more on this.) Most books that choose to measure angle of attack relative to the chord line violate their own rules when the flaps are extended, and continue to measure angles relative to where the chord of the unflapped wing would have been. That is illogical and creates confusion about how you should use the flaps. This is one of the reasons why it is advantageous to think in terms of absolute rather than geometric angle of attack.

Thinking about geometric angle of attack would be advantageous if you were *building* an airplane, or conducting wind-tunnel research on wing sections. Engineers can look at a wing section and determine the geometric angle of attack.

In contrast, if you are *piloting* the airplane, geometric angle of attack has no advantages and several big disadvantages: it’s hard to define, it’s hard to perceive, and it doesn’t tell you what you need to know anyway! We care about coefficient of lift, which is proportional to absolute angle of attack over a wide range (i.e. not too close to the stall). Each degree of angle of attack is worth about 0.1 units of coefficient of lift.

The simple rule “pitch plus incidence equals angle of climb plus angle of attack” (figure 2.2) is always mathematically valid, no matter what reference you’re using to measure angle of attack. (That’s because the arbitrariness in the angle of incidence cancels the arbitrariness in the angle of attack.) But if you want the rule to be *useful* in the cockpit, especially in situations where flap settings are changing (as discussed in section 5.5), you need to focus on absolute angle of attack.

2.15 Summary

- Trim for airspeed at 1 *G*.

- Trim for angle of attack! *Trim for angle of attack!*
- Fly with a light touch, so you can feel if you are pulling the aircraft off its trim speed.
- To make changes in angle of attack, lead with the yoke, then trim off the pressure.
- Pitch attitude is not the same as angle of attack. Angle of attack is what really matters.
- You can observe pitch attitude and direction of flight as a *means* for controlling angle of attack.
- The airspeed indicator gives you quantitative information about angle of attack (except near the stall).
- If the aircraft is producing a non-standard amount of lift, many (but not all) of the critical *V*-numbers must be corrected. The percentage change in speed is half the percentage change in weight.

1

Wind may affect what angle of attack gives the best angle of climb or best angle of glide; see section 7.5.7.

2

Changes in engine performance may slightly affect what angle of attack gives the best climb rate or best climb angle.

3

The *relative wind* is defined to be the speed and direction that the air is moving relative to the airplane. (It is very, very different from the velocity of the wind relative to the ground.) Unless otherwise specified, the relative wind is measured at a place where the airmass has not been greatly disturbed by the passage of the airplane. See section 2.11 for more details.

4

See section 19.6.2 for a more formal definition.

5

The effect of flaps is discussed in more detail in section 5.5. See also the table in section 12.11.

6

I am imagining a day without appreciable updrafts and downdrafts, so that the relative wind is horizontal; otherwise the story gets a little more complicated.

7

adjusting power if necessary to maintain level flight

8

Most people are right-eye dominant. If neither eye is strongly dominant, you can choose one arbitrarily and close the other when checking the sight line.

9

The meaning of true (versus calibrated) airspeed will be discussed in section 2.12.

10

Not sooner, since on most airplanes, power changes slightly affect trim speed.

11

Incidence is important too, but you rarely need to worry about it. It only changes when you are changing the flap setting.

12

I am glossing over the distinction between horizontal speed and total speed. The tables tabulate the tangent and arctangent, based on true horizontal and vertical motion. In a really steep dive, the airspeed indicator would indicate the total motion, which is the resultant of the horizontal and vertical components. If you really wanted to calibrate the angles against the VSI and the (total) airspeed, you should use the sine and arcsine. However, at any halfway reasonable angle, the difference is less than a percent or two. Don't worry about it.

13

See section 12.4.3, including figure 12.13, for an analogous discussion of angles relative to the *ground*.

14

The constant of proportionality is arranged so that at sea level, in standard conditions, the calibrated airspeed is identical with the true airspeed. Since you are almost always flying at altitudes above sea level, your true airspeed will almost always be larger than your calibrated airspeed.

15

... but beware: as discussed in section 2.12.6, there are cases where it is quite important to keep track of the distinction between IAS and CAS.

16

Load factor is defined in section 6.2.3. You don't need to worry about it except during aggressive maneuvers.

17

See section 12.11.3 for more on this and related topics.

18

In general, *clean* refers to something with small parasite drag. The *clean configuration* refers to flaps retracted, landing gear retracted (if possible), et cetera.

19

In other airplanes the static pressure is measured on a mast, far from the side of the fuselage, so this problem does not occur.

20

If you want to maximize gliding time instead of distance, or if you want to account for tailwinds and/or updrafts, see section 7.5.

21

The chord line is the straight line drawn from the leading edge to the trailing edge, as shown in figure 3.12.