The CIX VFR Club	Flight Training Notes	
For Simulation Purposes only. Not to be used for real World flight	THE BASIC THEORY OF FLIGHT	Issue 1.1 25/08/2012

1 INTRODUCTION

This tutorial is specifically designed for Microsoft Flight Simulator pilots flying VFR flight in the UK. It explains in fuller detail than does FS itself, the meaning and application of the basic performance data provided in the program, plus some additional information from the real world which is applicable to Flight Simulator.

This document explains the basic reasons why an aeroplane stays in the air, how it climbs and descends, and how it speeds up and slows down. The aircraft described in this tutorial is the FSX Cessna 172SP, but the principles apply to all fixed wing aircraft.

2 UNDERPINNING KNOWLEDGE

This section covers the pure science, the physics, which underpins the theory of flight, and although it is a benefit if you understand it thoroughly, an “overview understanding'' is sufficient. In the VATSIM Pilot Ratings Scheme, you are not expected to know the formulae, or which theory causes which flight movement.

2.1 Velocity

This is not quite the same thing as speed. (Technically it’s a “vector” which is speed in a given direction.) ATC often give “Vectors” to guide an aeroplane to the runway heading – these are often just the heading (direction), but they can also ask you to adjust the speed of your aircraft (this then makes it a “Vector” in the scientific sense!).

2.2 Newton’s Laws of Motion

First Law An object will remain at rest (or move at constant velocity) if there are no forces acting on it, or if the net forces are balanced. *It won’t move unless I push it! (And it still won’t move if someone else pushes against it equally but in the opposite direction!)*

Second Law If a force acts on an object it will either accelerate or decelerate:
(Force = mass x acceleration).
If I push it, it either speeds up, or if I pull it, it slows down!

Third Law To every “action” there is an equal and opposite “reaction”. *If I push or lean against a wall, the wall pushes against me – otherwise you’ll both fall over!*

2.3 Conservation of Energy

Energy cannot be created, or destroyed, but can be converted from one form to another.

There are two types of energy:

2.3.1 Potential Energy

This is energy that is stored in some way – e.g. a battery, or a tank of aviation fuel. It is also the energy of height because of the existence of gravity, known as "Gravitational Potential Energy", PE.

Gravitational Potential Energy is of prime importance to flight, because for an aircraft to fly some other energy has to be converted to Gravitational Potential Energy to put the aircraft in the air.

Mathematically, potential energy is expressed as:

$$PE = m \times g \times h$$

Or *Potential Energy = mass x gravitational acceleration x height*

Note: Gravitational acceleration "g" is a constant value – 9.81 metres per second per second ($9.81 m/s^2$), or 32 feet per second per second ($32 ft/s^2$) in imperial units. Anything which "falls" accelerates at this rate (if you ignore air resistance).

"per second per second" perhaps needs some explanation. The distance it falls is proportional to the elapsed time squared. An object starts to fall, and at the end of one second will be travelling at 32 feet per second. At the end of two seconds it will be travelling at 64 feet per second and after 3 seconds; 96 feet per second. It is gaining speed (accelerating) at 32 feet per second *every second*. Fortunately, you don't need to know that for basic flight, but is included in case you are interested.

2.3.2 Kinetic Energy

Kinetic Energy is the energy of motion, and is given by

$$KE = {}^1/_2 \times m \times v^2$$

(Kinetic Energy = 0.5 x mass x the square of the velocity).

2.4 Bernoulli's Theorem

In simple terms Bernoulli's theorem states that if an incompressible fluid is made to flow faster (travel further) then its pressure drops.

Although air is a gas and therefore compressible, at the speeds of flight the air is effectively incompressible. This has important implications in the design of aircraft wings.

So with that knowledge, we can look at how it applies in basic flight.

3 STRAIGHT AND LEVEL FLIGHT

In steady flight, i.e. straight and level at constant speed, Newton's First Law of Motion means that the forces which keep the aircraft UP must be in balance, and the forces which keep the aircraft travelling horizontally at constant speed must also be balanced. In technical language: -

- Lift is equal to the weight of the aeroplane
- Thrust is equal to drag

3.1 Drag

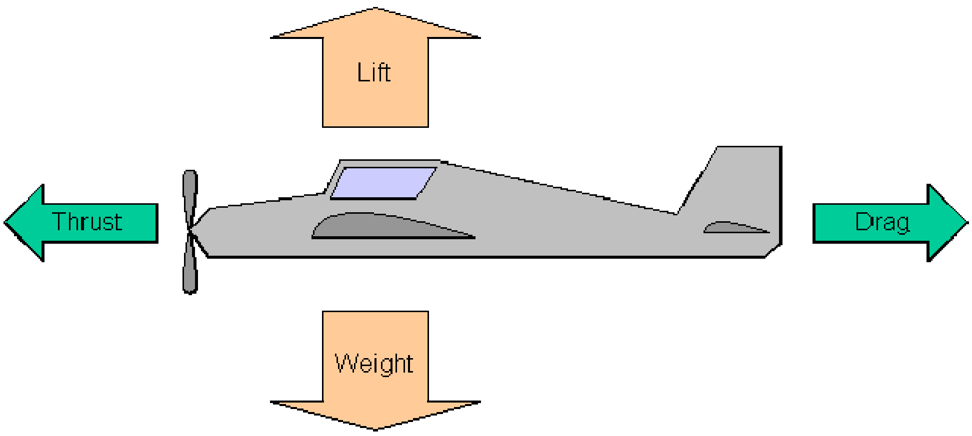
Drag cannot be avoided. It is a by-product of the aeroplane moving through the air. There are two types of drag.

- Induced drag – drag caused by increasing the wing frontal area (tilting it up a bit in the air flow in lay language), and
- Parasite drag – the drag due to the basic shape of the aircraft.

The major component of induced drag comes from the wings, and it is related to the airspeed and the "angle of attack". Parasite drag is affected only by the airspeed.

3.2 Thrust

This is provided from a source of "potential energy" carried on board the aeroplane - the fuel! The fuel energy is converted into thrust by the engine and propeller. The amount of energy converted is controlled by the throttle, which the pilot has to adjust until the thrust exactly equals the drag.



The Forces of Flight Diagram

3.3 Weight

This technically is the mass of the aeroplane (Plus pilot and fuel etc.) times the gravitational acceleration, g: -

$$W = m \times g$$

Although constantly decreasing slightly (as fuel is used up) it remains effectively constant for our purposes. The change of weight would become apparent on say a long haul flight across the Atlantic.

3.4 Lift

This has to equal the weight and is derived from the wings. It is related (like the drag) to both the "angle of attack" and the speed.

4 WHY "HEAVIER THAN AIR" FLIGHT IS POSSIBLE

4.1 History

At first it was thought that lift could only be achieved rather like a boat floats on water, by having a large "bag" of something that is less dense (lighter) than the surrounding air. They used "hot air", highly inflammable hydrogen (which was dangerous – remember the Hindenburg and R101 disasters) or inert Helium.

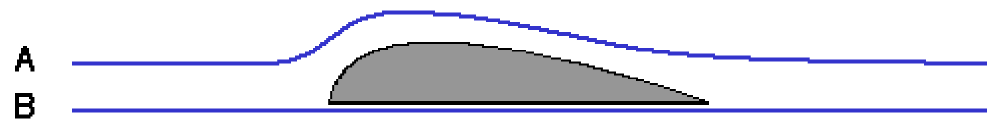
The scientists in those days ignored the inconvenient fact that birds (which are heavier than air) can fly!

4.2 How Lift is Created

Two of the Laws of Physics explained in Section 2 above, are responsible for the creation of lift; Bernoulli's theorem and Newton's Third Law of Motion.

4.2.1 Bernoulli's Theorem

Bernoulli's theorem shows that if the air passing the aircraft can be made to travel further over the top than underneath (and therefore travel faster) it will have a lower pressure. The difference in pressure between the top and bottom generates lift.



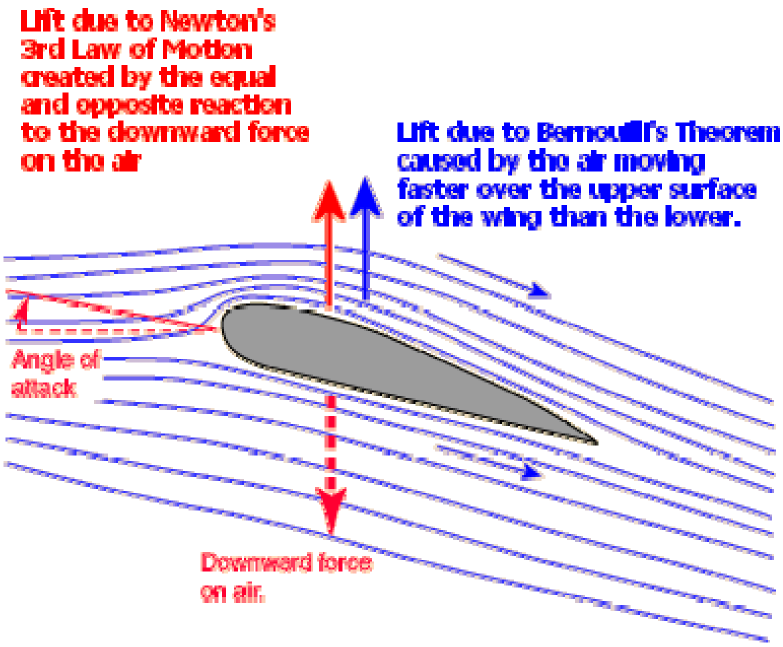
The air at "A" has to move further than that at "B".

Even if it doesn't quite meet up exactly with its partner after passing the airfoil it has still had to move faster! If it doesn't meet up exactly turbulent vortices are produced, and the energy used creating these vortices produces drag, which designers attempt to reduce to a minimum.

There is thus a difference in pressure between the top and bottom surfaces of the airfoil. It is this pressure "differential" that causes lift. In very simplistic terms the wing is "sucked" upwards!

4.2.2 Newton's Third Law of Motion

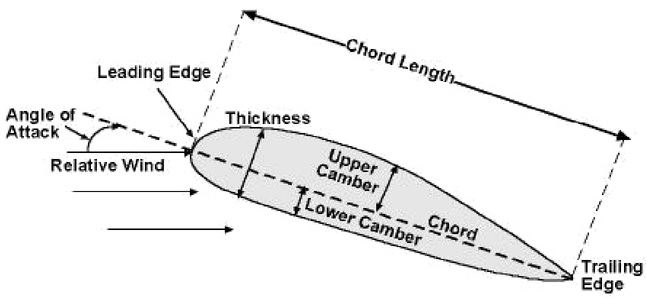
The wings of an aeroplane are attached to the fuselage at a slight angle. This angle deflects the air passing over it downwards. As air hits the underside of the wing, even in straight and level flight, it is forced downward, and because of Newton's Third Law of Motion, an equal and opposite upward force is therefore generated by the wing, contributing to the creation of lift.



There is debate about which of these two physical laws of motion has the greater effect, a debate which you do not need to join for Flight Simulator!

4.2.3 Angle of Attack

The angle of attack is the angle at which relative wind meets an airfoil. It is the angle that is formed by the chord of the airfoil and the direction of the relative wind or between the chord line and the flight path.



The angle of attack changes during a flight as the pilot changes the pitch of the aircraft, i.e. the degree at which the longitudinal axis is above or below horizontal.

Up to the point where the airfoil "stalls" (i.e. stops producing lift),

The lift L varies as the angle of attack α times the square of the speed υ

Mathematically:

$$L \propto \alpha \times \upsilon^2$$

This equation is vitally important to how an aircraft flies.

If the aircraft is to be maintained flying level, the lift must be maintained equal to the weight of the aeroplane. So changing the angle of attack <u>must</u> mean that the speed at which the aeroplane is flying must be changed. Conversely, if the speed changes, the angle of attack must be changed.

If an aircraft flies level, and its speed is increased (because the pilot has increased power) the speed of the air over the wings increases, so the angle of attack must be decreased to maintain the lift constant. If he does not decrease the angle of attack by lowering the nose slightly, the aircraft will climb.

Similarly, if the aircraft flies level, but slower, because the pilot has reduced power, the speed of the air over the wings decreases, so the angle of attack must by increased to maintain the same lift. If the pilot does not raise the nose slightly to increase the angle of attack, the aircraft will descend. The difference between nose-high slow flight and nose-low fast flight attitudes isn't great - normally less than 10^{o}.

5 CLIMBING AND DESCENDING

The following sections apply to aircraft with only a small margin of excess power. The rule is:

Attitude for airspeed and power for rate of climb or descent

It is the method of control taught since the days of the Tiger Moth, but there is a growing school of thought which believes that the rule should be:

Power for airspeed, attitude for rate of climb or descent

The debate continues. Certainly once you start flying larger aircraft, the second rule is that which is taught and used universally. There is an extremely good article on the Internet about this at

http://www.flight.org/blog/2010/02/20/attitude-for-airspeed-power-for-rate-of-descent

In your light aircraft, in the Cix VFR Club Flying School, you will stick to rule 1!

Attitude for airspeed and power for rate of climb or descent

5.1 Climbing

Let’s say you’re flying straight and level at 2000 ft and need to climb to 3000 ft, how do you do this?

Pull back on the joystick? – WRONG!!! This increases the angle of attack, so yes it does initially increase the lift and you climb slightly, BUT it also increases the induced drag so you slow down. Slowing down decreases the lift, so the aircraft does not climb.

Open the throttle? – YES. This does increase the speed slightly, BUT this in turn greatly increases the lift. (Remember that lift is proportional to the square of the velocity!) With the lift now greater than the weight you start moving upwards.

A more technical/scientific way of thinking of this is, you are putting in more power, (i.e. energy), but effectively keeping the speed the same and so not increasing the kinetic energy – the extra energy has to be converted to “Gravitational Potential Energy” and so you move upwards!

5.2 Descending

Let’s say you are now flying straight and level at 3000 ft and need to descend to 2000 ft, how do you do this?

Push forward on the joystick? – WRONG!!! This decreases the angle of attack, so yes it does decrease the lift and you dive slightly, BUT it also decreases the induced drag so you speed up. This increases the lift again, so you stop going down as fast.

Close the throttle? – YES**.** This does decrease the speed slightly, BUT this in turn greatly decreases the lift. (Remember that lift is proportional to the square of the velocity!) With the lift now considerably less than the weight you start moving downwards.

In practice, the rate of descent achievable at constant power without overspeeding is quite modest. The only way to descend in a controlled manner, at a controlled airspeed and at a descent rate of your choosing is to reduce power.

A more technical/scientific way of thinking of this is, you are putting in less power, (i.e. energy), but effectively keeping the speed the same and so not decreasing the kinetic energy – the extra energy has to be converted from our store of “Gravitational Potential Energy” and so you move downwards!

6 SPEEDING UP, AND SLOWING DOWN

6.1 Speeding up

Let's say you're flying straight and level at 70 knots and need to speed up to 110 knots, how do you do this?

Open the throttle? - WRONG!!! - Remember this does increase the speed slightly, BUT this in turn greatly increases the lift and so you start climbing.

Push forward on the joystick? - WRONG! This decreases the angle of attack, thus decreasing the induced drag so you speed up. But you will also start to descend slowly as the lift has been reduced by the lower angle of attack.

Open the throttle AND push forward on the joystick? YES! You must add power to overcome the parasite drag which results from increased airspeed, but you must lower the angle of attack to prevent the increase in lift which would otherwise also result from increased airspeed.

6.2 Slowing down

Let's say you're flying straight and level at 110 knots and need to slow down to 70 knots so you can deploy the flaps, how do you do this?

Close the throttle? – WRONG!!! – Remember this does decrease the speed slightly, BUT this in turn greatly decreases the lift. (Remember that lift is proportional to the square of the velocity!) With the lift now less than the weight you start moving downwards.

Pull back on the joystick? – WRONG! This increases the angle of attack, so yes it does initially increase the induced drag and you slow down, BUT you also climb slowly as the lift has been increased by the higher angle of attack.

Close the throttle AND pull back on the joystick? YES! You reduce power so that the parasite drag can slow the aircraft down, but you must also increase the angle of attack to compensate for the decrease in lift which would otherwise also result from decreased airspeed.

6.3 The Phugoid Response

If you pull back the joystick a fraction without changing the power, the aircraft immediately climbs a little due to increased angle of attack, but then as the airspeed decays because of lack of power to maintain that climb, the lift decays, and the nose will drop slightly. The airspeed will again increase, so the lift will also increase, so the nose will go up again. As the airspeed decays again, the lift also decays again, and the nose will drop slightly once more. The airspeed will once more increase, so the lift will yet again increase, so the nose will go up again.

This oscillation in pitch is called a phugoid response. In theory, it can go on indefinitely, but, like a pendulum, which eventually stops swinging in air (but would go on indefinitely in a total vacuum), is "damped" by the drag of the air.

The phugoid response is most dramatically illustrated, both in real aircraft and in Flight Simulator, if you establish level flight, trimmed out, then pull back the stick and let go. Eventually, after several oscillation cycles, the aircraft will continue flying level as before. In aircraft design, the phugoid response is designed to be damped out in 3 cycles. In flight simulator, Microsoft hasn't been quite that clever, and damping to neutral can take as many as 20 cycles.

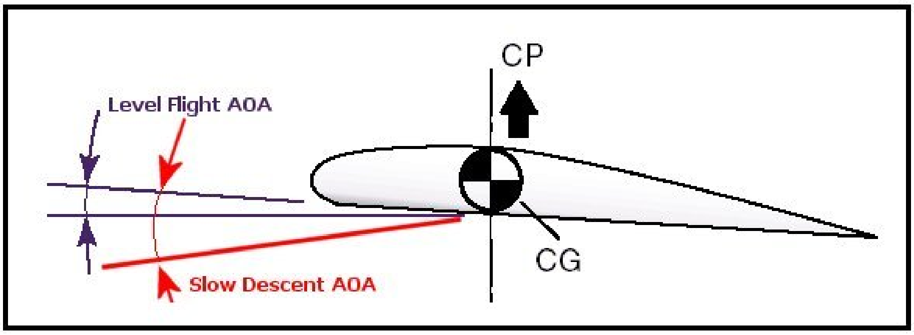
As a consequence, it is useful to make some control input to aid the damping. A small degree of opposite elevator input (nose going up – down elevator and vice versa) to reduce or neutralise the phugoid response is desirable, and well worth doing as a normal part of flying. So when you change power, be ready for the aircraft to over-respond in pitch, and make small corrections to kill the developing oscillation almost before it starts.

7 BEST GLIDE SPEED

What happens if your engine stops? This cannot happen "by accident" in Flight Simulator, only if you have set up some failure routines in the Menus. How do control the aircraft to reach the runway?

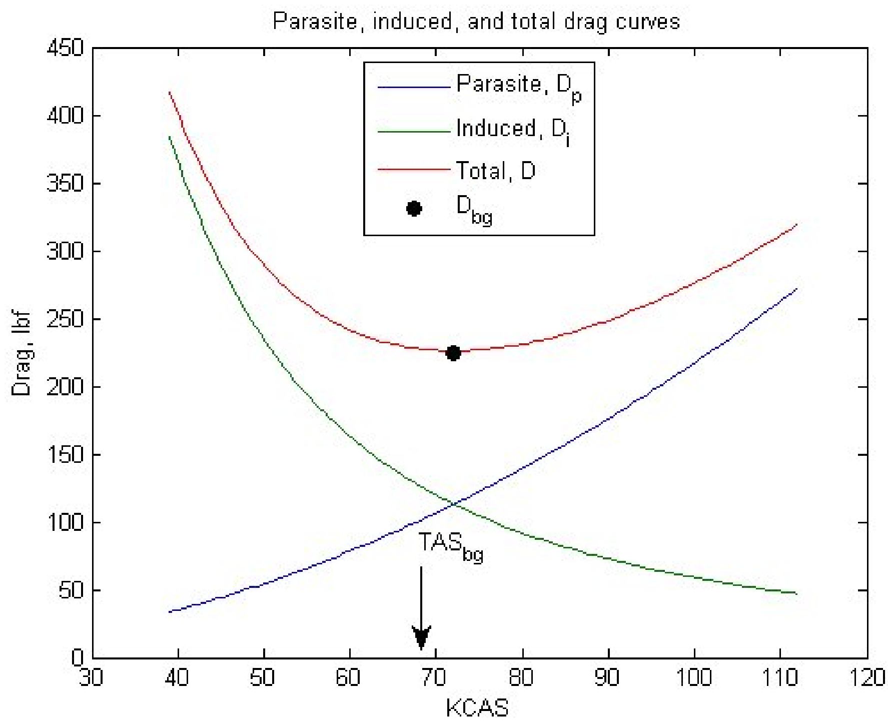
Most light aircraft have a glide ratio of about 9 : 1. This means that without power, and without flaps, if set to fly at the "best glide speed" it will fly 9000 feet horizontally and descend 1000ft vertically.

If, when the engine stops, the nose attitude is held level with a little back pressure on the joystick, you will slow down a little and the aircraft will start to descend because of a small loss of lift. The air flow is now from beneath the wings, and so the angle of attack (AOA) increases and lift therefore decreases further, and the aircraft descends more quickly.



If, however, you point the nose down and lower the angle of attack, you will reduce induced drag, gain a little airspeed and a little more lift and the aircraft will handle better – not so near the stall so better control response. But you will also increase parasite drag

There is an optimum between these two conditions, called the Best Glide Speed. We know that as the angle of attack increases, so does the induced drag. But parasite drag, the drag due to the basic shape of the aircraft reduces as airspeed reduces. The total drag (adding the two together) can be plotted on a graph against airspeed, and at the point where the combined drag is a minimum – that is the Best Glide Speed. This is because the aircraft will slow down less at that speed than at any other speed, and thus will descend less in a glide, in a given horizontal distance.



In the drag diagram for the Cessna 172SP above, Best Glide Speed (TAS_{bg}) is 68 knots. At 68 knots the Cessna 172SP will descend at a "Glide ratio" of about 9 : 1. This means that without power, and without flaps, if set to fly at the "best glide speed" it will fly 9000 feet horizontally and descend 1000ft vertically. Put another way, it will descend 700 feet per nautical mile. This is important information for estimating where the aircraft will land with no engine.