CHAPTER 14

NOTES ON AERODYNAMICS FOR PILOTS PREPARING FOR THE GPL EXAM

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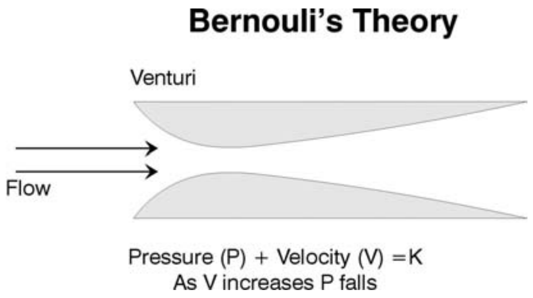
Lift and Drag

When an aerofoil moves relative to the air a number of physical effects occur simultaneously. These include:

1. The air flows more rapidly over the upper surface than under the lower surface.
2. The air pressure above the upper surface is reduced while the air pressure below the lower surface increases.
3. The wing exerts a force on the air flowing over and under it, deflecting the air downwards.
4. The air exerts a force on the wing. The component of this force that acts at right angles to the relative airflow is called “lift”. The component that operates in the direction of the relative airflow is called “drag”.



Note that effects (1) and (2) are related by Bernoulli’s theorem, which states that the sum of the static pressure and the dynamic pressure is constant:

$$P + \frac{1}{2} \rho V^2 = \text{Constant}$$

Where P is static pressure, ρ is the mass density of air, and V is relative velocity of the air with respect to the wing. The term $\frac{1}{2} \rho V^2$ represents dynamic pressure, which is the increased pressure of the air caused by its velocity.

Newton's third law of motion, which states that for every action, there is an equal and opposite reaction relates effects (3) and (4). Hence the force exerted on the wing by the air is equal and opposite to the force exerted on the air by the wing.

Lift and drag can be quantified by the following equations:

$$L = \tfrac{1}{2} \rho V^2 S C_L$$

$$D = \tfrac{1}{2} \rho V^2 S C_D$$

Where S is the surface area of the wing, and C_L and C_D are the *coefficient of lift* and the *coefficient of drag* respectively. These coefficients depend on the aerofoil section and planform of the wing and the *angle of attack*.

Angle of Attack

The angle of attack is the angle at which the wing meets the relative airflow. This is usually measured as the angle between the direction of the relative airflow and the *chord line*, a straight line through the extreme leading and trailing edges of the aerofoil section.

For a wing with a given aerofoil section and planform, the coefficients of lift is determined by the angle of attack. The following graph plots C_L against the geometric angle of attack, for a typical asymmetric wing section:

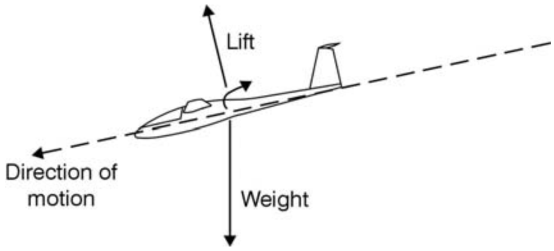
Note that C_L is positive when the angle of attack is zero. This is typical of an asymmetric wing section; however for a symmetric wing section C_L is zero when the angle of attack is zero.

The coefficient of lift increases with increasing angle of attack up to a maximum at the *critical* angle of attack, after which it decreases rapidly. When the angle of attack of a wing exceeds the critical angle of attack, the wing is *stalled*. Note that the critical factor that causes the wing to stall is its angle of attack, and not the speed of the relative airflow. A wing will stall at any airspeed if the angle of attack exceeds the critical angle of attack. However in level unaccelerated flight, the critical angle of attack will only be exceeded at low airspeeds.

Note that the position of the control stick gives a good indication of the angle of attack at which the wing is operating. If the control stick is central, the wing is operating at a low angle of attack. The further back the control stick, the higher the angle of attack of the wing.

Forces acting on the Glider in Flight

The *weight* of the glider acts vertically downwards. *Lift* acts at 90 degrees to the direction of motion relative to the surrounding air. *Drag* acts opposite to the direction of motion relative to the surrounding air.



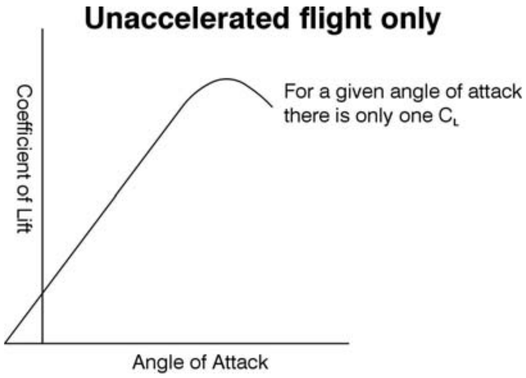
In un-accelerated flight, when the glider is travelling at constant speed in a straight line, these forces must cancel each other out. This means that the vector sum of all the forces acting on the glider is zero. (Otherwise in accordance with Newton’s laws, the resultant force would cause the glider to accelerate, either changing its airspeed or its direction of motion).

We can draw these forces in a triangle to show that the sum of the forces is zero. Note that in normal gliding (descending) flight, lift is always slightly less than weight as a component of drag also acts vertically upwards, helping to oppose the weight of the glider. However for typical gliders, this effect is negligible and it may be assumed that the vertical component of lift is approximately equal to the weight of the glider.

We can also superimpose a second triangle showing the *glide ratio*, the ratio of the horizontal distance travelled to the height lost. Note that these are both right-angled triangles, and that the angle marked as θ is the same in both triangles. Hence the triangles are congruent, which means that the ratio of the lengths of the corresponding sides is the same for both triangles, and it follows that the *glide ratio* is identical to the *lift/drag* ratio.

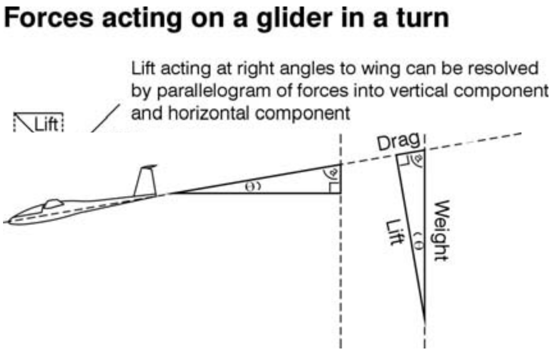
Note that the glide ratio does *not* depend on the weight of the glider, only on the lift/drag ratio.

Note that the angle of attack during unaccelerated flight depends on the airspeed. The higher the airspeed, the greater the lift generated for any given value of C_L, hence at high airspeeds a lower value of C_L is required to generate sufficient lift to counteract the weight of the aircraft. Since a low value of C_L corresponds to a low angle of attack, it follows that *in unaccelerated flight only* low airspeed means a high angle of attack, and high airspeed means the wing is operating at a low angle of attack. This is why *in unaccelerated flight* stalls occur at low airspeed.



Forces Acting During a Turn

When the glider is banked, the lift vector can be divided into two components: one that acts horizontally towards the centre of the turn, and one that acts vertically upwards.



Since the vertical component of lift must still be sufficient to counteract the weight of the glider, the total lift generated must be greater in a turn than during level flight. In order to increase the lift generated without increasing airspeed the pilot must increase the angle of attack of the wing. This requires a backward movement of the control stick, which is why we apply back-pressure during a turn. If we do not apply back-pressure the attitude of the glider will change (i.e. the nose will lower) thus increasing speed to generate the additional lift required *(see also Spiral Instability).* Effectively therefore we try to maintain our original attitude and this requires backpressure on the control stick.

One effect of "pulling Gs" – whether while turning or during a pull-up manoeuvre – is to increase the airspeed at which the wing will stall. The reason for this can be from the lift equation:

$$L = ½ \rho V^2 S C_L$$

When the wing is operating at the critical angle of attack, we have

$$L = ½ \rho V^2 S C_{L\ Max}$$

Where $C_{L\ Max}$ is the coefficient of lift at the critical angle of attack. Because the lift is equal to the weight multiplied by the G factor,

$$G\ W = ½ \rho V_S^2 S C_{L\ Max}$$

Where G is the G Factor, W the weight and V_S the stall speed.

Rearranging we get

$$V_S^2 = G\ W / (½ \rho S C_{L\ Max})$$

Which shows that the stall speed is proportional to the square root of the G loading. (Note that it is also proportional to the square root of the weight). During a turn with a 60° bank angle, the G factor is 2.0, so the stall speed is 1.41 times the stall speed in unaccelerated flight.

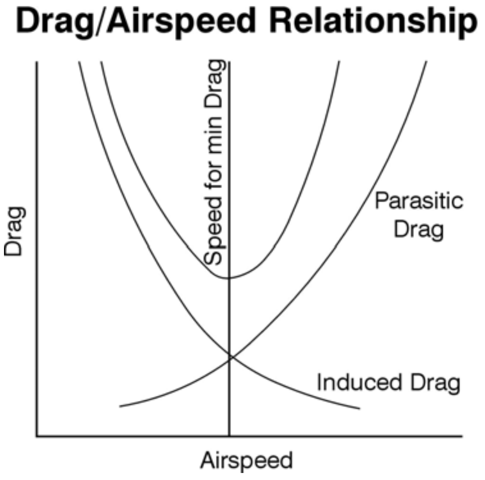
(The G force in a turn is related to the bank angle by the following equation:

$$G = 1 / \cos \theta$$

Where θ is the angle of bank. The proof is left as an exercise for interested students).

Sources of Drag

Induced Drag, also known as *Vortex Drag* is caused by the wing vortexes generated at the wing tips as the high pressure air below the lower surface of the wing flows around the wing tip to the low pressure area above the upper surface of the wing. Because induced drag depends on the pressure differential between the upper and lower surfaces of the wing, and because this pressure differential is greatest at high angles of attack, induced drag increases with increasing angle of attack. Because high angles of


Drag/Airspeed Relationship

attack correspond to low airspeed, induced drag is greatest at low airspeeds and decreases with increasing airspeed. Induced drag is inversely proportional to the square of the airspeed.

Form Drag is caused by the pressure variations over the aircraft as it moves through the air. *Skin Friction Drag* is caused by the contact of the air with the aircraft's surfaces. *Form Drag* and *Skin Friction Drag* always occur together and are jointly known as *Profile Drag*. *Interference Drag* is caused by joints between different surfaces – such as the wing/fuselage joint – which usually cause additional drag over and above that expected by simply adding the drag caused by the one surface to the drag caused by the other surface. These types of drag increase with increasing airspeed, and are proportional to the square of the airspeed. (Note that sometimes Interference Drag is omitted from discussions, in which case the term *Profile Drag* may be taken to include all types of drag other than Induced Drag).

The total drag is the sum of the Induced Drag (which is inversely proportional to the square of the airspeed) and the other types of drag (which are proportional to the square of the airspeed). The minimum total drag always occurs at the airspeed where the Induced Drag is equal to all other forms of drag combined.

Adverse Yaw

When the aircraft is rolled into a turn using the ailerons, the aileron on the outside wing is deflected downwards while the aileron on the inside wing is deflected upwards. This increases the camber of the outside wing, causing it to generate more lift, and decreases the camber of the inner wing causing it to generate less lift. The differential lift generated is what causes the glider to roll. However effectively increasing the wing camber will also increase the drag (as the penalty for lift is drag) and this will cause the aircraft to yaw in the opposite direction from the desired turn. This is known as *adverse yaw*, and is corrected by using rudder in the same direction as the aileron inputs.

Adverse Yaw: Differential ailerons

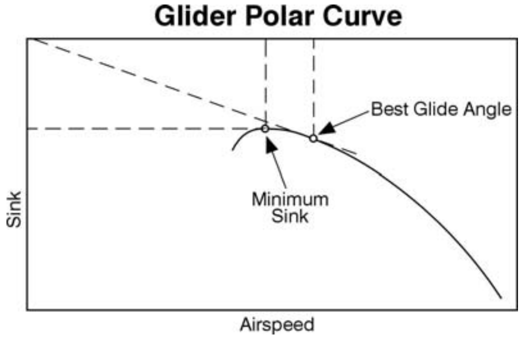
Differential ailerons are designed to make upgoing ailerons move through a greater angle than downgoing to increase drag to counter adverse yaw.

Most modern gliders use *differential ailerons.* These are designed so that the down-going aileron moves through a smaller angle than the upgoing aileron. This reduces the additional drag caused by the downgoing aileron, reducing adverse yaw.

Another approach to reducing adverse yaw is *Frise ailerons.* With these the leading edge of the upgoing aileron has an extension ahead of the hinge line which impinges into the air stream to increase drag on that side, counteracting the increased drag caused by the downgoing aileron on the other side.

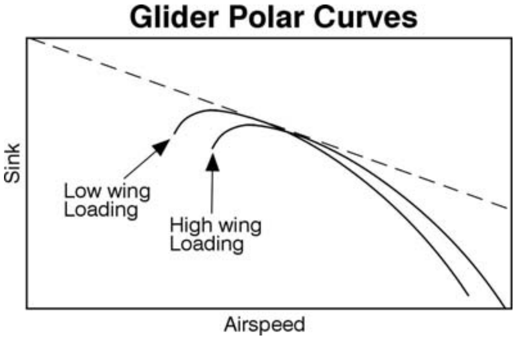
The Polar Curve

The effect of drag on a glider is to cause it to descend in unaccelerated flight. The *polar curve* shows the rate of descent plotted against airspeed. The following chart shows a typical polar curve.



Note that the rate of sink is fairly high at speeds near the stall speed, decreases to a minimum (known as the *minimum rate of sink* for the glider) with increasing airspeed and then increases with further increases in the airspeed.

A commonly used (although in my opinion not particularly useful) figure of merit for gliders is *best glide ratio*, which is also known as *L/D max* since the concepts of *glide ratio* and *lift/drag ratio* are equivalent as illustrated earlier. This is the ratio between the horizontal distance flown and the height lost during unaccelerated flight in still air. Since the horizontal scale on the polar represents the distance flown in unit time, and the vertical scale represents the height lost in unit time, the glide angle at any airspeed can be found by drawing a line from the origin to the point on the polar curve corresponding to that airspeed. The best glide angle can be found by drawing a line from the origin which only just touches the polar curve (mathematically this line is described as being a tangent to the polar curve) as shown on the polar above. Note that it will not touch at the point that represents the minimum rate of sink, but at a point on the polar corresponding to a somewhat higher airspeed. This is the airspeed for best glide.



Effect of Wing Loading on the Polar

The *wing loading* is the total weight of the glider (including the pilot and any ballast) divided by the surface area of the wing, and is usually expressed in Kg/m^2. As the wing loading is increased (for example, by adding water ballast) the polar curve is shifted downwards and to the right. The minimum sink rate will increase, as will the airspeed at which the minimum sink rate occurs. However the amount that the curve shifts to the right and the amount that it shifts down are related in such a way that the best glide ratio will remain the same, even though the speed for best glide and the sink rate at best glide will both increase with increased wing loading. (This assumes that the best L/D ratio remains the same irrespective of wing loading. In practice the best L/D and hence the best glide ratio tends to increase slightly at higher wing loadings due to Reynolds number effects. However this falls outside the scope of these notes).

Stability

Pitch or *Longitudinal Stability* refers to the tendency of the glider to maintain a given angle of attack and airspeed if the elevator position remains the same. The horizontal stabilizer is an aerofoil that operates at a lower angle of attack than the main wing. If the aircraft pitches up, then the angle of attack of both the wing and the horizontal stabilizer is increased by the same amount. However the effect is proportionately greater for the stabilizer, which started out with a smaller angle of attack, than for the wing, and hence the stabilizer generates relatively more lift (or less down force) in the pitched up attitude than it did in the original attitude. The additional lift (or reduced down-force) from the stabilizer tends to return the aircraft to its original trimmed angle of attack and airspeed. Note that if the centre of gravity is behind the rear limit then the glider may become longitudinally unstable.

Weathercock Stability refers to the tendency of the glider to align its direction of movement so that it meets the relative airflow straight on. If the glider is yawed then the vertical stabilizer, which is itself a symmetric aerofoil, meets the relative airflow at a non-zero angle of attack and generates a horizontally acting “lift” force which acts in the opposite direction to the yaw.

Roll Damping refers to the tendency of an aircraft to resist rolling moments. When an aircraft begins to roll, the downward going wing meets the relative airflow at a greater angle of attack than the upward going wing. As long as the wing is not stalled, this will cause the downward going wing to generate more lift than the upward going wing, counteracting the rolling force.

Spiral Instability is the tendency of the aircraft when turning to steepen its bank and lower the nose, resulting in a spiral dive if left unchecked. When the aircraft is turning, the outer wing is moving faster than the inner wing and hence generates more lift. The unequal lift forces will cause the turn to steepen, which reduces the vertical component of the lift vector, causing the nose to drop. As the nose drops the airspeed increases and the overbanking tendency becomes more pronounced. As the speed and angle of bank increases, the G force also increases and if left unchecked this is likely to cause structural failure. The correct recovery from a spiral dive is first to level the wings using the ailerons, and once the wings are level to restore the normal flying attitude using the elevator. Note that attempting to pull out of the dive before levelling the wings will only serve to steepen the bank angle and may hasten structural failure.

Stalls and Spins

If the angle of attack of the wing is allowed to exceed the critical angle of attack, the glider is stalled. The amount of lift generated by the stalled wing is reduced, while the amount of drag generated will increase. The reduced lift will cause the nose of the glider to drop. The initial effect of the nose dropping is to further increase the angle of attack, although as it drops below the horizontal the angle of attack will begin to reduce until it is below the critical angle of attack and the glider is no longer stalled. The correct recovery procedure is to check forward on the control stick in order to reduce the angle of attack and to prevent a secondary stall.

If the glider is yawed when it is stalled, then the effect of the yaw is to increase the angle of attack of the inner wing and reduce the angle of attack of the outer wing. This causes the inner wing to become more deeply stalled, generating more drag and less lift. Similarly the outer wing is less deeply stalled, generating less drag but more lift than the inner wing. The result is that the inner wing will drop, further increasing its angle of attack, and the outer wing will rise, decreasing its angle of attack. At the same time, the glider will yaw more towards the inner (dropping) wing due both to its increased drag and due to the weathercock effect as the glider slips towards the lower wing. Simultaneously, the reduce lift generated by the stalled wings will cause the nose to drop. These effects reinforce each other, and the combined yawing, banking, diving motion will continue until it is stopped.

Spin recovery consists of first applying full rudder opposite to the direction of the spin. This halts the yawing motion, which in turn will allow both wings to stabilize at the same angle of attack so that both wings generate the same amount of lift and the rotation will stop. When the rotation stops - or after a distinct pause if the rotation does not stop – the stick should be moved forward to reduce the angle of attack and unstall the wing. Once the rotation has stopped the rudder should be centralized and the glider eased out of the dive using normal control movements.

Note that it is important not to move the stick forward immediately as in some aircraft a neutral or down elevator may blank out the rudder during a spin, making the rudder ineffective so the rotation will continue even with full opposite rudder. If the centre of gravity of the glider is behind the rear limit then recovery may be impossible.

The Effect of Flaps and Airbrakes

Applying positive flap (i.e. deflecting the flap downwards) increases the effective camber of the wing. This will increase the coefficient of lift for any angle of attack before the stall. It also increases the maximum lift coefficient although the angle of attack at which this is achieved – the critical angle of attack – will usually be decreased. Drag is also increased by positive flap settings, although small positive settings incur only a modest drag penalty. Positive flap settings are used for thermaling and landing as the increased coefficient of lift available with a positive flap setting decreases the stall speed. It is inadvisable to reduce the flap setting near the ground, as the consequent loss of lift will result in a loss of height.

Airbrakes act to reduce the coefficient of lift and increase the coefficient of drag for the wing. Because the coefficient of lift is reduced, the airspeed at which the critical angle of attack is reached (the stall speed) will be increased when the airbrakes are used, typically by around 5 km/h.

Andrew Roos

(See also Appendix ii – Suggested Reading: **Internet:** – “How Airplanes Fly”

Graphics by David Starke