BASIC SAILPLANE AERODYNAMICS: PART 4

INTRODUCTION

How did you react to Article 1 in the July addition of *Soaring Australia*? Do you think wings suck, push or pump, or all of these and more?

Still unconvinced? Maybe you are clinging to the Bernoulli-based theory that the majority of lift comes from suction created by the airflow over the top of the wing. If so, think about this: how is sustained inverted flight possible? Perhaps there is something to Coanda and the 'wing as a pump' theory after all…

No matter; two things are certain: wings produce lift and the aerofoil shape of the wing has a profound influence on sailplane performance.

LIFT (continued)

This article looks further at sailplane LIFT and wing aerodynamics. It also deals with DRAG – the fourth of the forces acting on a sailplane in flight. You will remember from the previous article that the others are: LIFT, WEIGHT and THRUST.

Aerofoils

The main progress in sailplane performance over the years has come from refinement in aerofoils and the strength, lightness and design flexibility allowed by modern airframe materials.

An aerofoil is any shape designed to produce lift. It has a leading edge, a trailing edge, a chord and camber (see Figure 8). Aerofoils have infinitely superior lifting properties and much less drag compared to the flat plate design of early wings. As well as superior lift over drag performance, aerofoils produce greater lift when the speed of the airflow is increased. The curvature of the top and bottom surfaces of a wing defines the shape of the aerofoil. The degree of curvature is called the upper and lower wing cambers.

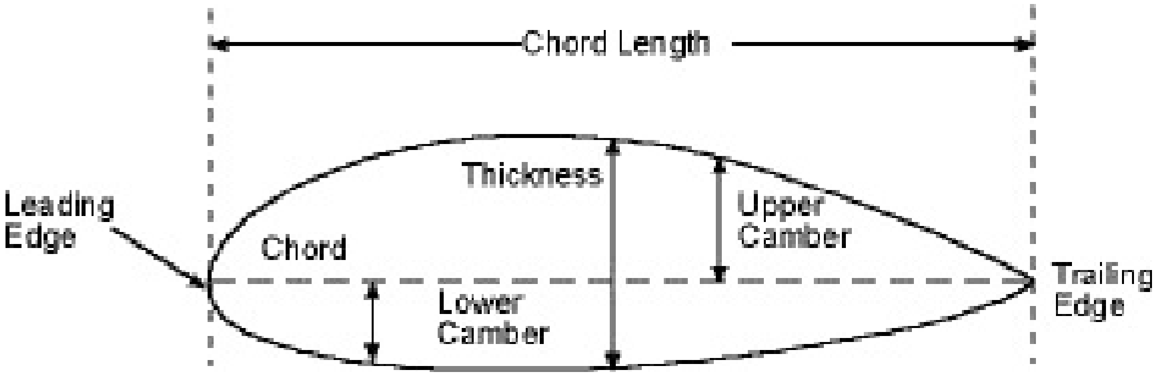
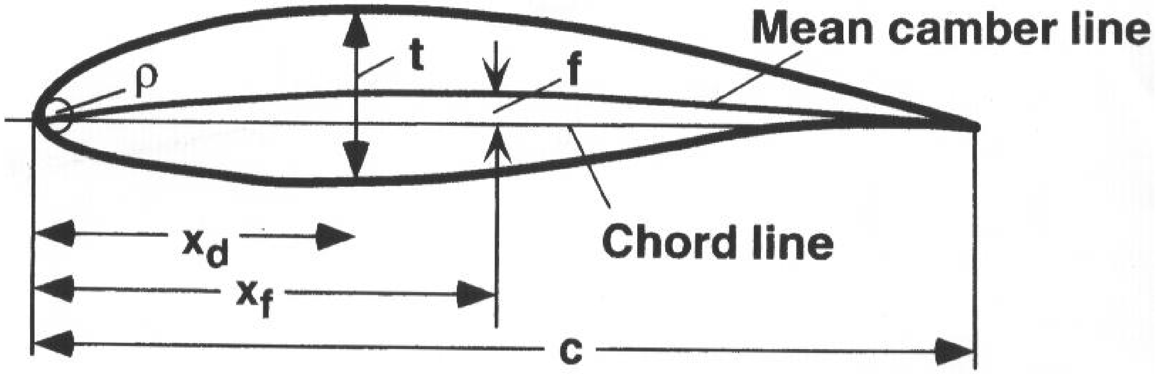


Figure 8: Basic aerofoil

An aerofoil's characteristics can reasonably be defined by the parameters of chord, maximum thickness, position of maximum thickness, mean camber (line equidistant between the upper and lower surfaces), point of maximum camber and the leading edge radius.



t Thickness

x_d Point of maximum thickness

f Camber

x_f	Location of maximum camber
p	Leading edge radius
c	Chord

Figure : 9 Aerofoil Parameters

Glider Aerofoils

Early glider designs used simple aerofoils shaped to produce a high lifting force at low speeds. These were well suited to slope soaring and climbing in weak thermals. Better understanding of the atmosphere’s soaring potential and the desire for gliders to be capable of high speed flight over long distances stimulated a shift towards more sophisticated aerofoils.

Low speed performance naturally remained a priority and modern sailplanes are capable of exploiting very weak lift – although, generally at higher airspeeds than their pioneering counterparts. The real gains have been at the high speed end.

Here are some examples of this evolution:

GÖTTINGEN 682
(minimum drag and high lift co-efficient – designed for slow speed flight)

GÖTTINGEN 549
(less cambered and maximum thickness further aft – good high speed performance and pleasant stalling characteristics)

WORTMANN FX 62-K-153
(low drag – designed to maximise the laminar flow effect in the boundary layer) [see Part 3 for boundary layer]

Figure 10: examples of glider aerofoil sections (Source: Welch and Irving, *New Soaring Pilot)*

Wings and The Boundary Layer

Flow Around a Wing

When air flows over a solid body such as a wing, viscosity causes the air closest to the wing to slow down. In fact, the air actually in contact with the wing is stationary relative to the wing. The air in the layer just clear of the surface is moving slowly, and the next layer a bit faster. Eventually, at some distance from the wing, the effects of viscosity are so slight that the air is all moving at the same speed. The air near the wing which has been slowed by viscosity is called the ***boundary layer***.

The Boundary Layer

The ***boundary layer*** is the sandwiched zone containing all the air between the wing surface and the point where the layer reaches 99% of its potential free stream velocity. Boundary layers can be laminar, turbulent or separated.

In general, a ***laminar*** boundary layer will be thinner than a turbulent boundary layer. In laminar airflow each layer of air slides smoothly over the layer below even to the point it is in contact with the viscous layer sticking to the surface.
If the flow is turbulent, friction results in a sheet of rolling eddies, or vortices, in the flow along the surface. The result is a thicker boundary layer.

Airflow over a wing up to its thickest point is generally laminar. Beyond that point the air flow in the boundary layer generally becomes turbulent. In modern glider design the trend is towards aerofoil sections which have their thickest point well aft. This is to maximinise the area of laminar flow.

Turbulent or separated, as opposed to laminar, flow in the boundary layer wastes energy in generating the eddies. This causes extra drag. However, while a turbulent boundary layer is thicker and causes more drag that a laminar boundary layer, it has one important advantage. Because of the eddies in a turbulent boundary layer, it is more energetic and tends to stick to a surface longer than a laminar boundary layer.

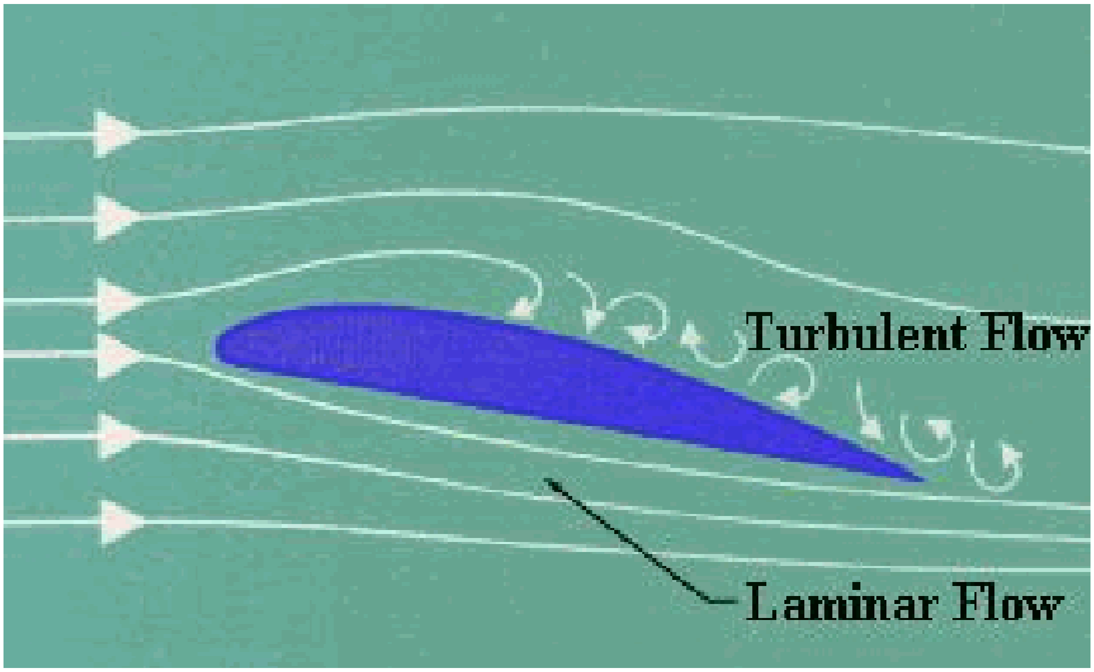


Figure 11: exaggerated depiction of turbulence in the boundary layer (the boundary layer is actually very thin ; eddies can also form in the boundary layer under the wing)

Maximising Laminar Flow

The extent to which laminar airflow can be maintained around the wing's surface is key factor in improving aerofoil performance. Modern sailplanes employ elegant, highly refined aerofoils designed to maximise laminar flow. This is particularly evident in FAI 15 metre Racing Class and Open class where very thin aerofoils are used. Most have a maximum thickness of 12.7% of the chord.

A good example is the ETA – the world's biggest sailplane. The fundamental objective behind the design of the ETA was to maximise extraction of energy from the air with the absolute minimum of lift-related drag. This incredible aircraft has a six piece 30.9 metre wing and reputedly delivers a best glide of more than 60: 1, possibly as much as 70: 1. It uses 3 different aerofoil sections – root (HQR 1), main span (HQR 2), and outer span (HQR 3).

Figure 12**:** ETA sailplane aerofoil section HQR 2 (Source: Simons M, *Sailplanes 1965 – 20*00*).*

Laminar Separation

Laminar flow is very sensitive to disturbances and changes in velocity. It breaks down when the flow velocity starts to slow down, usually around the point of maximum thickness on the upper wing surface and further aft on the lower surface. Even with the most refined aerofoil, airflow tends to break away at some point from the wing's surface. Generally, the further aft the point of maximum thickness the greater is the likelihood of the flow separating from the surface. In some cases the flow may re-attach to the surface creating a laminar separation "bubble" and in other cases the separation may be absolute.

Laminar separation happens without transition to turbulent flow, but it does create very high drag with associated loss of lift. Designers work hard to prevent laminar separation. Typically, this is achieved by creating a forced transition to a turbulent boundary layer by using turbulators to disturb the airflow at the point where the separation bubble would otherwise form. Turbulators will be covered in more detail in a later article.

Stalling

Most sailplane aerofoils ***stall*** at roughly the same angle of attack – between 15^0 and 16^0. Airflow at less than the stalling angle generally remains attached, reflecting the laminar flow characteristics of the particular aerofoil section. Beyond the critical angle of attack, air cannot flow effectively around the leading edge and over the wing's top surface without separating. The wing consequently loses much of its ability to produce lift and a wild turbulence of eddies creates considerable drag. On a well designed aerofoil the separation starts near the trailing edge and progressively moves forward as the angle of attack increases. This gives predictable and manageable stalling characteristics.

When the stall occurs, the airflow around the wing looks like this –

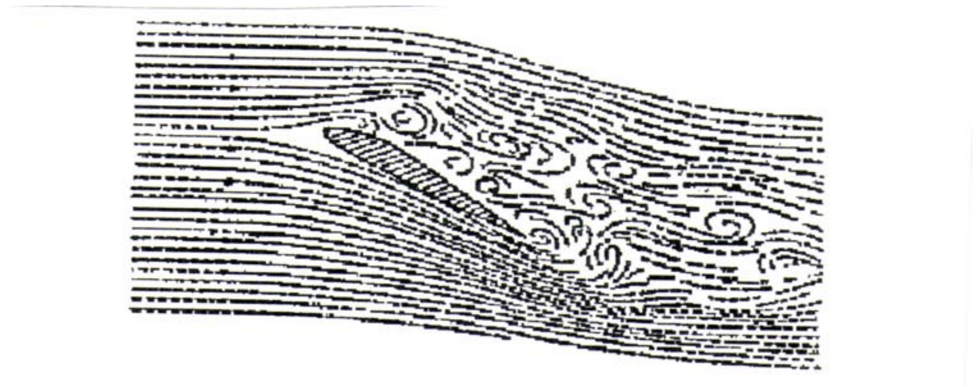


Figure 13: airflow around a stalled aerofoil (Source: Gliding Federation of Australia *Instructor's Flight Reference Cards*)

WING LANGUAGE

Wing terminology has remained virtually unchanged over the years.

Key **A - B:** **Chord line**

C: **Chord**

∝: **Angle of attack** – which is the angle between the chord line and the airflow direction

R: Force resulting from air striking the chord line (exact position of "**R**" is variable depending on the angle of attack)

D: **Drag** - which is parallel to the airflow direction

L: **Lift** – which is at right angles to the airflow direction

CP: **Centre of Pressure**

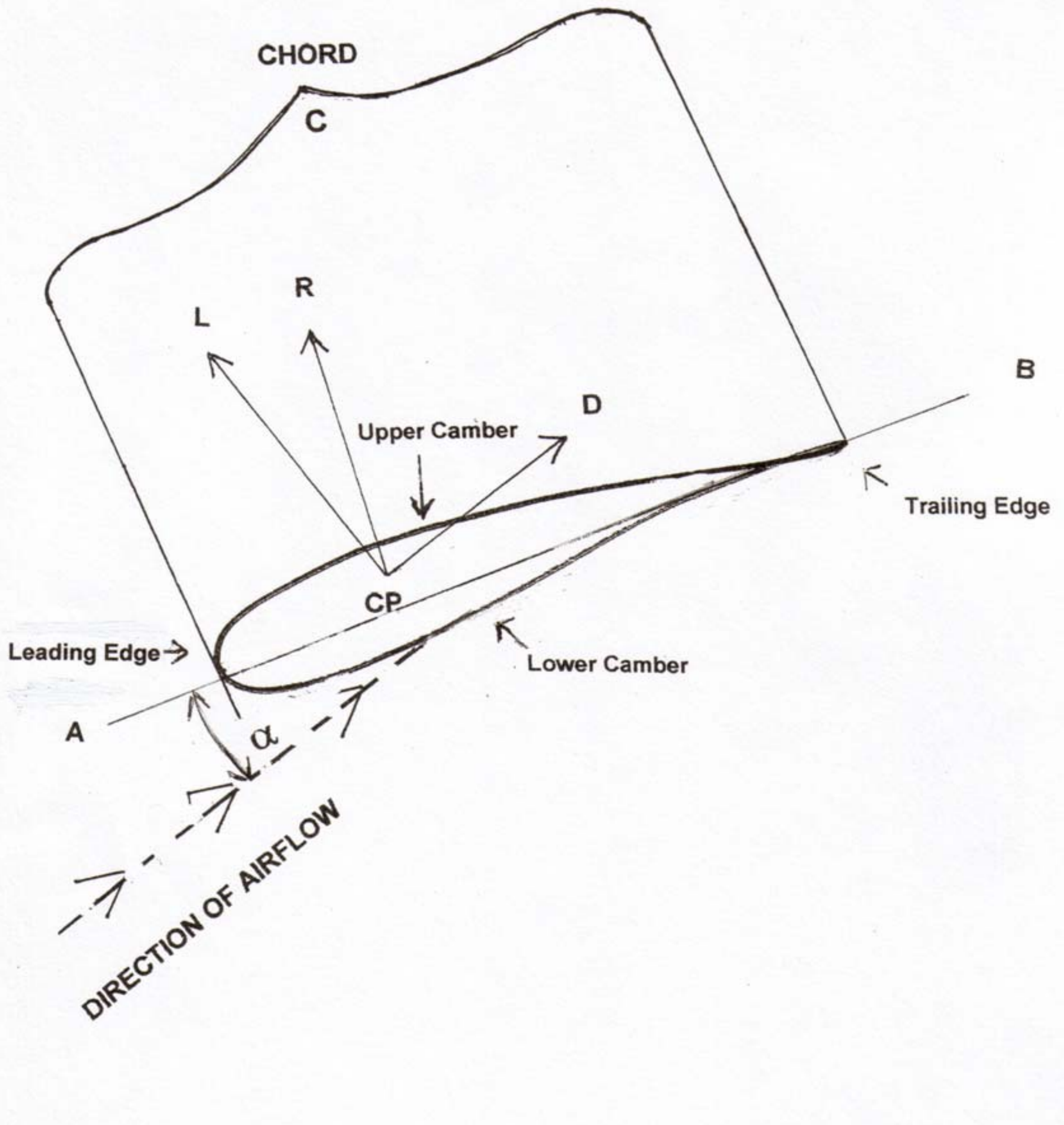


Figure 14: Basic wing terminology

Some Key Concepts.

In addition to aerofoils, laminar flow, the boundary layer and stalling there are some other key concepts that make it easier to understand wing aerodynamics. These are: centre of pressure, Reynolds Number, wing loading, aspect ratio, chord, taper and drag.

At some risk of oversimplication, they can be summarised along the following lines.

Centre of Pressure

The point of the aerofoil on which the combined forces of ***lift*** and ***drag*** acts is called the *Centre of Pressure.* The CP shifts according to the angle of attack at any given time. Consequently it needs to be factored in when examining issues of stability and control.

Reynolds Number

Reynolds Number is a dimensionless quantity expressing the ratio of inertia forces to viscous forces in fluid flow. It is an important factor in measuring boundary layer and aerofoil behaviour. You could say that the Reynolds Number is a measure of the way that viscosity and the size and airspeed of an aerofoil interact.

Glider aerofoil sections can be fairly sensitive to Reynolds Numbers. Because of this, when comparing the characteristics of glider wing sections, it is important to do so at the correct Reynolds Number corresponding to airspeed and size of each wing.

Wing Loading

Wing Loading is calculated by dividing the weight of the glider into the area of the wing. It is usually expressed in kilograms per square metre or pounds per square foot. For any given aerofoil and wing area, a higher wing loading means that the minimum sinking performance of the glider is degraded; but, at the same time, the best glide performance is obtained at a higher speed. A high wing loading is a distinct advantage for speed flying in strong lift conditions.

Chord

As shown in Figure 13 the **Chord** of a wing is the straight line distance between the leading and trailing edges. For sailplanes, as for most aircraft, the Chord is wider at the wing root and tapers towards the wing tip.

Aspect Ratio and Taper

The **Aspect Ratio** is the ratio between the wingspan and the average chord of the wing. The long slender wings of sailplanes result in high aspect ratios. The higher the aspect ratio of an aircraft of given weight and wing span, the higher will be the wing loading. **Taper** reflects the change in Chord from wing root to wing tip.

Twist

Wing tip **Twist** is used by designers to improve handling characteristics near the stall and to reduce drag. The angle of attack at the wing tip is designed to be less than at the wing root. This ensures that the wing tips operate at a lower angle of attack and are more lightly loaded than the inner wing. Consequently they will stall only after the inner part of the wing has stalled. This reduces the likelihood of entering into an inadvertent spin.

Incidence

The angle between the chord line of the wing and the longitudinal axis of the sailplane (or some other reference line) is called the “Rigger’s Angle of Incidence”. Most aircraft have a slight positive rigger’s angle of incidence so that the wing sits at a positive angle of attack when the aircraft is flying close to level. In the vast majority of sailplanes, this is not adjustable without major structural work.

The angle between the incoming airflow and the wing’s chord line is called the Angle of Attack. In these days of aircraft with fixed rigger’s incidence, the terms Angle of Attack and Angle of Incidence tend to be used interchangeably.

Wings in Summary

For sailplane pilots, the main aerodynamic considerations of wings are:

- Wings work because air has resistance and is a viscous fluid

- Aerofoils deflect air downwards resulting in the wing being pushed upwards. They also accelerate airflow over their top surface thus decreasing pressure and creating upward “suction”.

- The more extensive the laminar flow, the more efficient the wing

- The lifting effectiveness of an aerofoil increases with the angle of attack of the aerofoil – until a point is reached (about 15^0) when the aerofoil “stalls”.

DRAG

Any lifting surface moving through air will encounter resistance called ***DRAG***. So, to achieve flight, it is necessary not only to overcome the weight but also the drag of the flying object.

Let’s not forget Newton’s Laws. For steady flight in a straight line (equilibrium) the laws of motion dictate that there must be forces which exactly balance both the **WEIGHT** and **DRAG** of the aircraft. **LIFT** balances **WEIGHT**. **THRUST** balances **DRAG**.

OK, that’s all very well you might say – but so what? Well, remember, **THRUST** comes from converting hard-won height (potential energy) into distance and speed (kinetic energy). **So**, the less thrust needed to overcome drag, the more energy there will be available for glide performance. The essential message is: minimise the energy loss caused by **DRAG.**

Sailplane *drag* falls into two main categories: ***induced*** and ***profile***.

7 Induced Drag

Induced drag is a result of the wing “pushing” air downwards in order to produce lift. Near the wingtip the air tends to flow outward from the high pressure zone below the wing into the low pressure zone above. This flow creates a rotation which forms a trailing vortex behind the wing. More than 70% of the total drag generated by a modern sailplane in slow flight comes from wing tip vortices. At higher speeds the proportion is far lower.

Induced drag is inversely proportional to the square of the airspeed and density of the air. In simple non-mathematical terms, lift generates induced drag and the greater the angle of attack the more will be the drag. Other considerations aside, the larger the aircraft and the denser the air, the higher will be the induced drag.

The theoretical best wing design for minimal induced drag comes from elliptical spanwise distribution of lift. Unfortunately, this is not always compatible with other desirable characteristics such as simple construction, good handling near the stall and minimal profile drag. The Discus and SZD 55 sailplanes are examples of the efforts of sailplane designers to achieve as near an elliptical wing shape as possible. Wing twist can also be employed for the same purpose but is not as obvious to the unaided eye.

Photo: The elliptical Discus wing

(Photo: Rick Agnew)

Some aerodynamicists consider it possible to reduce induced drag with an elliptical form of dihedral which can be achieved by curving or bending the wings upwards. This also has the effect of reducing vortex drag. Some sailplanes, particularly those with large wingspans or very flexible wings like the ASW 20, do this naturally in response to increasing flight loads. The Discus 2 is an example of a using polyhedral wing design to attain the same result in a Standard Class sailplane with a fairly rigid wing.

Without doubt, the most popular advance in reducing wingtip vortex drag lies in the use of winglets. Not only do they reduce energy loss through drag but they also generally improve flight handling characteristics at low speeds. And, of course, they look GREAT! Winglets will be dealt with in more detail in a later article.

Photo: Pilot’s View of Discus leading edge and winglet

(photo: Colin Vassarotti)

8 Profile Drag

Profile drag is essentially skin friction. It occurs because of air viscosity and the fact that a sailplane can never be so perfectly streamlined as to eliminate completely all air resistance. The aircraft literally drags air along with it in flight. Profile drag is proportional to the square of the speed of the aircraft. So the faster you go the greater the profile drag penalty.

Glider designers strive mightily to minimise profile drag. Improvements in extending the laminar boundary layer, not only over the wings, but the entire airframe, have been the main source of enhanced glider performance over the last thirty years or so. Modern glider construction materials and technology have allowed the achievement of extremely smooth surfaces, very accurate wing profiles, elegant fairings of airframe joints and minimal control surface gaps, including around airbrakes.

The fuselage is a significant generator of profile drag; but there is very little scope for reduction beyond what has been achieved so far. Pilot comfort sometimes suffers in the search for the narrowest possible fuselage profile. There is room for improvement in the design and positioning of the wing-to-fuselage and fin-to-horizontal stabiliser joints. Another possibility is to eliminate the horizontal stabiliser and/or the fin, although past attempts to build sailplanes without these have met with limited success.

An additional component to profile drag is called ***form*** drag. This occurs because the airflow around an aircraft does not close in neatly behind the tail and trailing edges of the horizontal surfaces. Rather it separates and forms a wake. The more streamlined and thinner the aerofoil and front end profile of the glider the lower will be the *form* and *profile* drag.

Total Drag

The total drag on an aircraft is the sum of induced drag, form drag and profile drag. Induced drag is inversely proportional to square of airspeed, and Profile and Form Drag are directly proportional to the square of airspeed. Hence, at low speed, induced drag will dominate, while at higher speed, form and profile drag will be the dominant form. At some speed, the two forms of drag will be equal, and this just so happens to be the point of minimum drag.

As the lift has to equal weight, the lift produced by a glider in steady flight does not change, so the Lift over Drag Ratio (L/D) is at a maximum when drag is at a minimum. Figure 15 shows how graphing the drag curves produces a shape called the “Drag Bucket”.

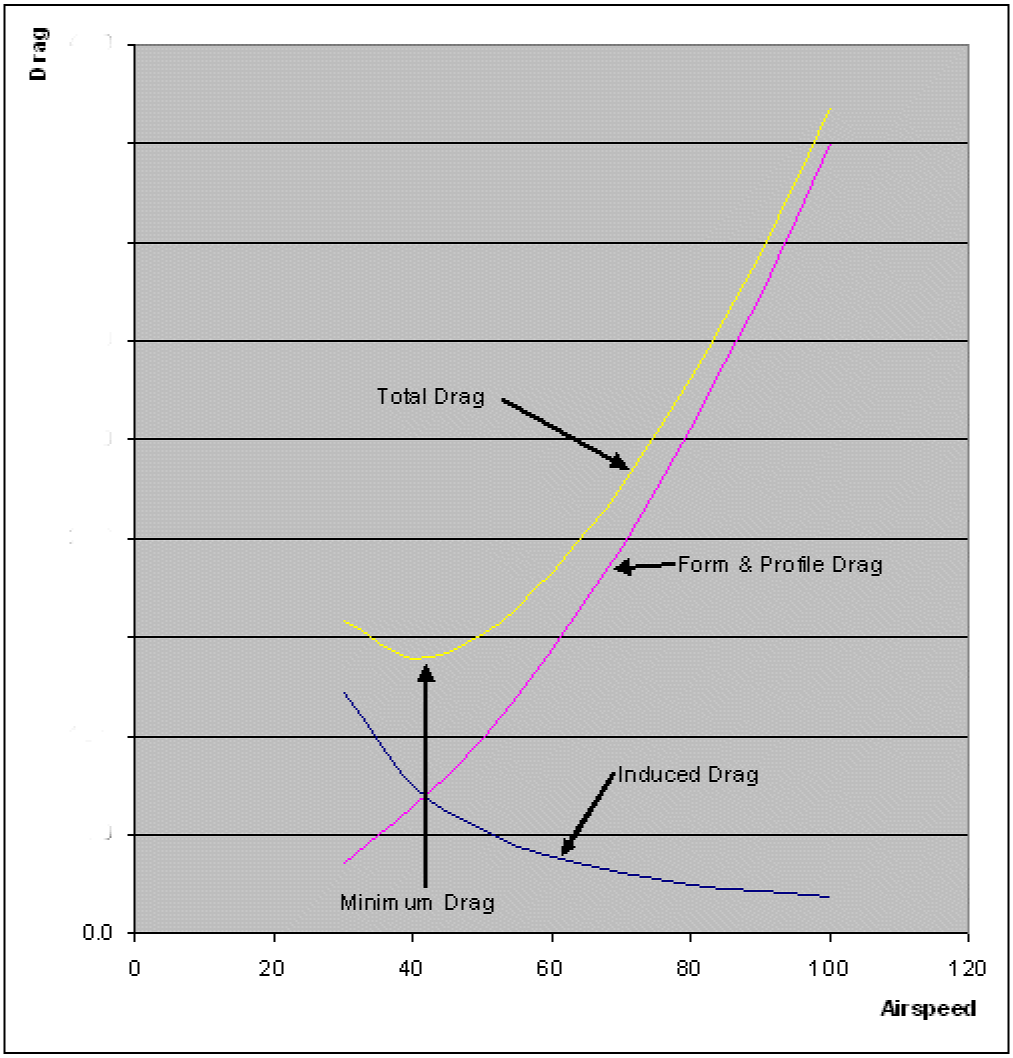


Figure 15: The “Drag Bucket”, in this example illustrating best Lift/Drag at 42 knots

More on Aerofoils

Variable Aerofoil Shapes

The camber and performance of an aerofoil can be varied by the use of flaps. Some flaps simply change the shape to create more lift allowing better low speed performance. Flaps of this type have the potential to vary wing area and consequently, wing loading. The Fowler flaps of the L13 Blanik allow excellent handling at quite low airspeeds which is one of the reasons the type first flown in 1956 has remained a popular trainer for half a century.

A high performance example is the SB -11 sailplane in which Helmut Reichmann won the 1978 World Championships at Chateauroux. This aircraft used large Wortmann flaps which could change the wing area from 10.56 to 13.2 square metres. The concept has not been taken much further, probably because the gain in performance was only marginal compared to other, and less expensive, 15 Metre Racing Class aircraft.

“Reflex” or, more correctly, simple trailing edge camber changing flaps give the best of both worlds. They allow the aerofoil profile of a wing to change from high lift at positive flap settings, to a high speed profile at negative flap settings. For slow circling flight the wing assumes a deeper camber producing high lift (and increased drag) . For cruise, a negative flap setting changes the lifting characteristics of the wing and decreases drag.

Reflex flaps change the pressure distribution around the wing, reducing significantly the tendency of a wing to pitch nose-down. Reducing this tendency means that less “downwards lift” is needed from the tailplane, which in turn reduces the lift the wing has to produce. This lighter load on the wing and tail results in less drag and higher performance.

Some pilots add weight to the tail to reduce the horizontal stabiliser drag at higher speeds. This is because shifting the CG aft brings it closer to the CP, thus reducing the length of the moment arm of the pitching force. The net effect is that less lift and accordingly less drag is produced by the tailplane, increasing performance overall. A note of caution though: flying with an aft CG potentially involves serious risks; some sailplanes, for example the Standard Cirrus, should never be flown at maximum aft CG.

Figure 16**:** Reflex Flaps illustrated

ACKNOWLEDGEMENTS AND FURTHER READING

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Correction

The "missing figure" from paragraph 9 of Article 1: 15 (pounds per square inch).

CV

Next Article In This Series: STABILITY AND CONTROL