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Virtuous circle

The development of composite fibre sailplanes

This article is based on the lecture given by Peter Hearne to the Royal Academy of Engineering in May 2002, and traces the development of sailplanes from the early roots in the 1920s and 30s, through the revolution of composite structures in the 1950s, to the superships of 2000 which are capable of lift to drag ratios of 70. The engineering behind this evolution in performance is described and a look into the enabling technologies of the future is attempted.

Before I describe the evolution of gliders over the past 100 years it will be useful to define a 'figure of merit' used to measure gliding performance – the lift to drag ratio (*L/D*):

$$\text{lift to drag ratio} = \text{weight to drag ratio} = \text{angle of glide}$$

For cross-country gliding flights, the higher the *L/D* ratio the better, as this allows the glider to cover more distance before having to find another thermal to climb in, or a field to land in!

The performance of a sailplane can be described in terms of a 'speed polar', which is simply a graph showing the sinking speed of the sailplane as a function of airspeed.

In addition to the requirement for a high maximum *L/D* ratio, the sailplane pilot also desires high values of *L/D* across as large a speed range as possible, typically between 40 and 120 knots, as this enables very long distance flights to be completed, and gliding competitions to be won. Gliding competitions are speed races held over fixed courses of up to 750 km where the only sources of energy available to the pilot, apart from the aeroplane tow at the start of the flight, are updraughts created by the heating influence of the sun. Despite the capricious nature of the weather and with gliders often flying over inhospitable mountainous or desert

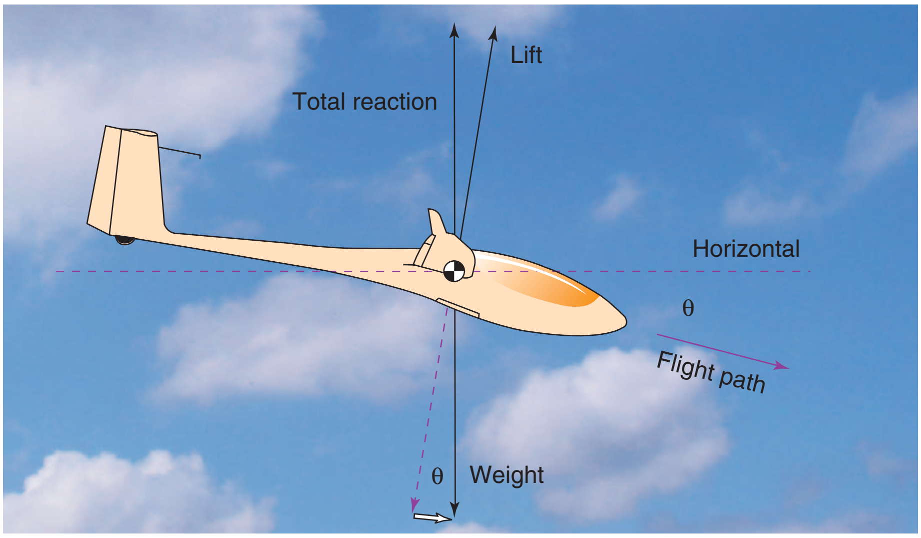

Figure 1 Gliding flight (courtesy of Steve Longland)

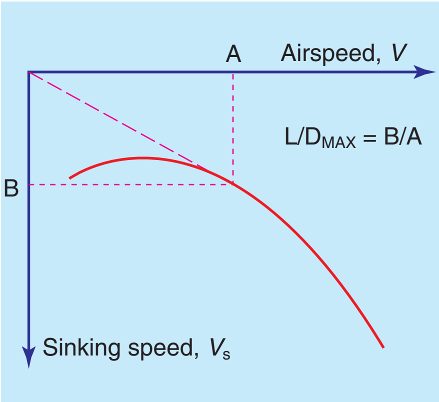

Figure 2 The speed polar

terrain, speeds of 130–150 km/h are routinely achieved during top-level competitions. Gliding is a sport where the UK is seriously successful: in 2001, five out of ten World Championship classes were won by British pilots together with three out of ten silver medals, a feat not achieved in any other British sport.

The design drivers that determine the *L/D* ratio are:

- wing span
- wing aerofoil shape
- fuselage shape and wetted area
- surface waviness
- weight

all of which are critically dependent on the airframe construction material. Surface waviness and finish are crucially important to achieving laminar flow in the viscous 'boundary layer' of air adjacent to the surface of the glider – if the surface is too wavy or rough the laminar boundary layer will be tripped into a turbulent state with a large increase in drag.

The first documented glider was the Cayley 'man-carrying glider' of 1853. This device had a large wing composed of a sail attached to a wooden framework, which took up its lifting aerofoil shape only in an airflow. Control was achieved by vertical and horizontal tail surfaces connected to the 'pilot' – actually Cayley's erstwhile coachman, as Cayley was 80 years of age – by a wooden tiller as in a sailing boat.

Whilst Cayley's glider did fly for a short distance, his achievements were quickly forgotten after his death in 1857 and despite the efforts of Lilienthal in the 1890s and the Wright brothers in 1900–02, it was not until the late 1920s that practical gliders were produced and available to the everyday 'club' pilot. Typical of this early generation of sailplanes is the beautiful Minimoa, designed by German pilot Wolf Hirth in 1936.

It was an advanced machine for its time, featuring a cantilevered wing rather than the strut-bracing which was common on the gliders that preceded it. The wooden structure was fabric-covered and the wingspan was close to the practical limit for wood at 17 m with an aspect ratio of 19. (Aspect ratio is a measure of the slenderness of the wing and is equal to wingspan^2/wing area.) The wing section used was the very thick Gottingen 601, and possessed limited laminar flow, leading to a modest maximum *L/D* of only 28. Besides giving low performance, the wooden structure required highly skilled craftsmen to build it and was vulnerable to handling damage.

Aerodynamic design techniques progressed rapidly during World War 2 and aerofoil sections capable of significant laminar flow were available to sailplane designers immediately after the war was over in 1945; however, these proved impractical with the wooden structures in use at this time as the small lumps and bumps on the surface of the glider tripped the laminar boundary layer into a higher-drag turbulent boundary layer. Even extensive filling and profiling of the structure was only partially successful due to the instability of wooden structures caused by temperature and humidity variations. What was needed was a much smoother surface.

The breakthrough was initiated in Germany in 1952, when Stuttgart Akaflieg began studying laminated paper/balsa core sandwich structures for sailplane use. This system failed to meet the necessary strength requirements, but in 1955 the paper was replaced by woven glass fibre cloth and the construction method for all modern composite aircraft was born.

The first glider to make use of glass fibre reinforced plastic was the Akaflieg Stuttgart fs-24 Phoenix, designed by the brilliant German designers Richard Eppler and Hermann Nagele. The Phoenix was a conservative design but even so had a maximum *L/D* of 38 which exceeded all wooden gliders that had preceded it.

Figure 3 Minimoa glider of 1936

Figure 4 The fs-24 Phoenix

Before we move on in this story, a few words on the Akafliegs or 'academic flying groups'. The incomparable Akafliegs are special sub-departments of German university technical faculties in which interested students and staff take part in the whole process of concept, design, manufacture and testing of cutting-edge state-of-the-art sailplanes, over a five- to seven-year period. The Akafliegs combine:

- enthusiastic young scientists and engineers who are active participants in the sport with a high level of personal achievement
- ability and opportunity at an early career stage to explore new advanced technology without the constraints of commercial risk
- the mature support and guidance of older faculty members who are usually ex-Akaflieg members
- support from local industry which benefits from technology developed within the Akaflieg and from employment of ex-Akaflieg students upon graduation
- a nursery for the types of skills an advanced country needs in the twenty-first century.

The success of the German Akaflieg system can be seen not only by the success of the German sailplane manufacturing industry, which is world-leading, but also in ex-Akaflieg members who are active in senior management of the German aerospace industry. It is a system that should be encouraged in the UK by partnership between academia and industry.

Returning to our story, the smooth surfaces available using composite structures had unlocked the performance of laminar flow wing sections whilst at the same time providing higher tensile strength and stiffness that allowed larger wingspan gliders to be built. In addition, the smooth wing surfaces were stable over the long term, reducing the maintenance requirement compared with the ageing wooden gliders.

The early 1960s saw a proliferation of glassfibre sailplane designs in the German Akafliegs including the Braunschweig SB6 of 1961 designed by Bjorn Stender and his team. Stender went on to design the BS-1 sailplane, similar to the D-36 described below, which went into production in 1966. Meanwhile the H-301 Open Libelle designed by Wolfgang Hutter and Eugen Hanle became the first composite glider to be mass-produced with 100 built between 1964 and 1969.

Another significant glider in our story was the very advanced Akaflieg Darmstadt D-36 'Circe' of 1965. Whilst the 17.8 m wingspan of the D-36 had raised the *L/D* to 44, the D-36 was important because it pioneered the use of trailing edge flaps to increase the performance at high speeds between 70 and 90 knots, where the flap was deflected upwards to increase the extent of laminar flow over the lower wing surface. Flaps have become a standard design feature on high-performance sailplanes ever since. The manufacturing methods used in production of the Phoenix remain basically unchanged today due to the high price and repair difficulty of more modern techniques such as autoclave-cured pre-impregnated (pre-preg) materials. The benefits of pre-preg over traditional wet lay-up carbon fibre composite structures are tabulated below:

Figure 5 The D-36 Circe

	Wet lay-up	Pre-preg
Weight	100%	95%
Strength	100%	110%
Fibre volume	60%	70–75%
Cost	1	2 or 3
Repair ease	Moderate	Complex

Table 1 Benefits of pre-preg over wet lay-up for carbon composites

Carbon fibre pultrusions with their higher material allowables are beginning to be used in gliders such as the world's largest glider, the 30.8 m span Eta. A pultrusion is formed when structural fibres are drawn through a heated die together with resin which polymerises, forming a composite material with very closely controlled fibre volume and orientation.

The Eta wing has an aspect ratio of 51.3 and a maximum *L/D* of 70, and is easily the most efficient aircraft conceived by mankind to date.

Besides improvements in material science, great advances have been made in aerodynamics to maximise the extent of low-drag laminar flow over the wings, fuselage and empennage of a glider such as the Eta.

Modern computation fluid dynamics (CFD) software has been used to design both the 2-D wing aerofoil section, as well as the more complicated three-dimensional regions such as the wing-fuselage fairing and wingtip. Subtle changes in wing aerofoil shape in the wing root region reduce the triangular shaped turbulent 'wedge' of airflow to reduce drag. At the wingtip, optimised winglets reduce lift-induced drag by up to 5%, further boosting *L/D* higher.

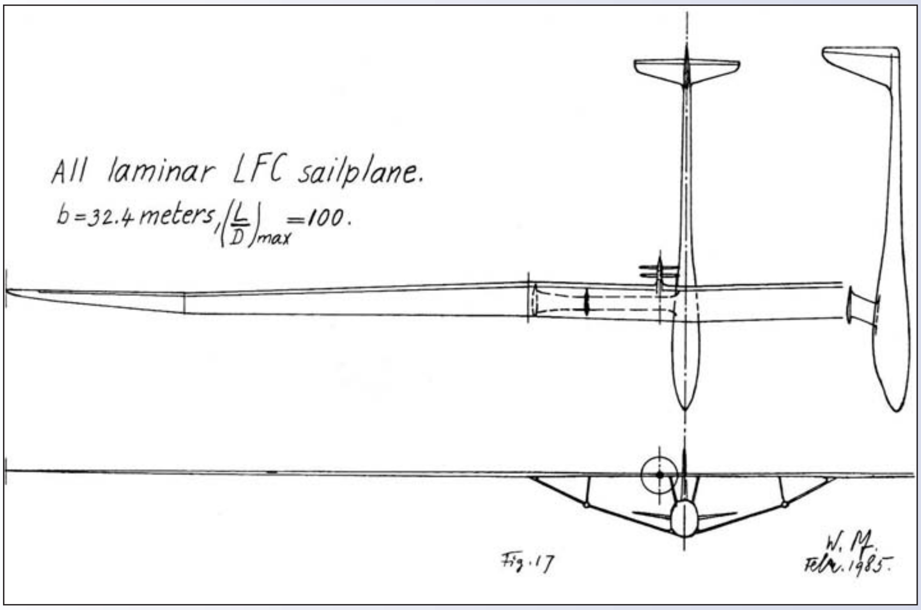

Figure 6 Pfenninger's 100:1 *L/D* glider design of 1985

With currently available technology, glider performance has reached a plateau, and ever enlarging the wingspan to increase *L/D* leads to gliders that are impractical to handle on the ground. A recent design exercise undertaken by students at Delft University of Technology in Holland has shown that to reach an *L/D* of 100 the wingspan must be increased to 42 m! A technology leap is required.

The technology leap most likely to occur will be boundary layer suction, probably using solar-powered suction pumps to suck away the turbulent boundary layer that exists over 40% of the typical glider. Whilst a design for a similar glider was proposed in 1985 by Walter Pfenninger (although this design used a windmilling propeller to drive the boundary layer suction pumps rather than solar cells), the manufacturing costs involved mean such a glider cannot be produced today at an affordable cost.

Promising developments are under way however, such as pneumatic drilling of tiny holes through solar cell material, again at TU Delft, that will allow such a sailplane to be produced at moderate cost.

Boundary layer suction sailplanes will offer the opportunity to smash the existing world gliding distance record which currently stands at 3008 km, with the potential of flying 4000 km in one day without the use of an engine. It is interesting to note that with such a 100:1 glider, the scale of the world's weather systems becomes the limiting factor to flying big distances in gliders. The high pressure systems which produce good thermal conditions for gliding are around 1000 km across, only allowing a triangle of 2600 km to be flown; greater distances can be flown in mountain standing wave systems as used to set the current distance record.

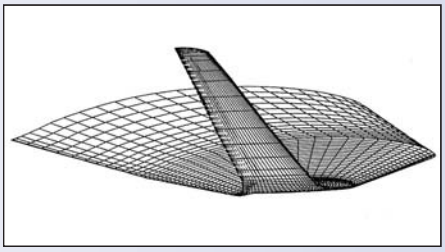

Figure 7 CFD mesh for a sailplane wing-fuselage winglet junction

Summary

The development of the high performance sailplane over the last 100 years has closely followed engineering advances in structural materials and aerodynamics. A virtuous circle driven by composite construction led to smooth and stable structures, which in turn encouraged the development of more efficient laminar-flow wing sections. Reduction in wing drag spurred designers to make advances in other areas such as retractable undercarriage, moveable flaps on the wing trailing edge and addition of large quantities of water ballast that would have been impractical with wooden structures.

The threefold improvement of sailplane *L/D* ratio between the early 1920s and 2000 has enabled pilots to experience flights that would not have been possible before – including flying into the stratosphere to set the world height record of 48,500 ft or high above the Andes to fly 3008 km in one day without the use of an engine.

Further aerodynamic, structural and manufacturing advances are foreseeable and will occur within the next 50 years; for the sailplane pilot the prospect of the 100:1 *L/D* glider is a something to savour and will enable outstanding long-distance flights to be completed. The limit may well be the geographical scale of our weather patterns rather than our application of advanced engineering in sailplane design.

Afandi Darlington is a Chartered Engineer, having graduated from Imperial College with an MEng degree in aeronautical engineering in 1995. After working for Airbus UK for five years, culminating as team leader for high-speed wing design on the A380 airliner, Afandi now runs Optimal Aerodynamics Ltd, a consultancy company focused on delivering aerodynamic design and analysis services to the aerospace and automotive industries. Afandi is a glider pilot and current member of the British gliding team.