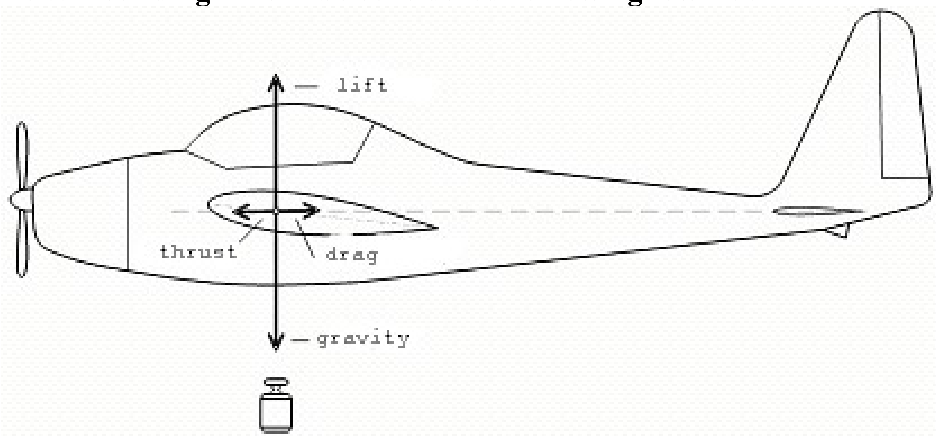
How does a conventional aircraft fly?

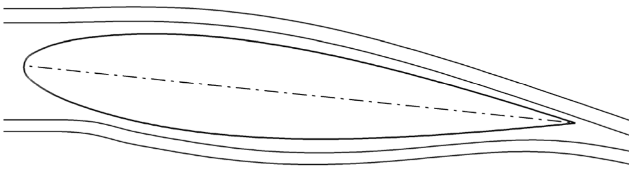
by Klaus Niegratschka/Bruno de Michelis

It does by the sum of several factors which work against the force of gravity. To achieve this, the aircraft has to proceed forward through the air, which flows around it and its wings as a consequence. The airplane's lifting area is diverting the surrounding air, creating a vertical supporting force. If we consider the aircraft as static, the surrounding air can be considered as flowing towards it.

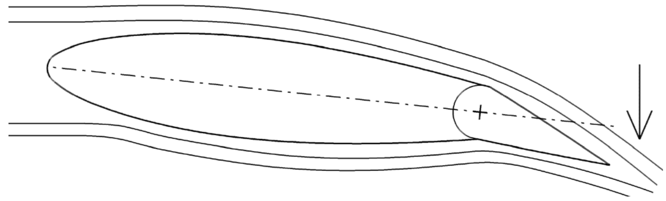


LIFT

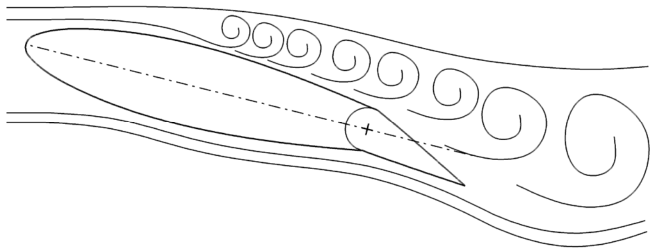
Let us consider a symmetric wing profile. The air flow will tend to follow the upper surface of the airfoil (Coanda effect, boundary layer attachment) and will be diverted according to the positive angle of attack (the angle between the profile's chord and the relative wind). On the lower surface, the diversion will be mainly created by the stagnating pressure.



The mass of the inert air particles opposes the dynamic change created by the diversion of the air flow. This generates a change both in density and pressure. At the upper surface of the wing, a negative (lower) pressure created by the air flow's higher speed will develope, while on the lower surface of the wing a positive (higher) pressure, generated by the air flow's lower speed, will appear: their combination will generate lift (vertical change of impulse of the airflow). This phenomenon follows the principle of conservation of linear momentum, as a compensating factor to the lifting surfaces (every action creates an equal and opposite reaction).
In addition, for any positive angle of incidence (the angle between the chord of the profile and the horizontal line of the aircraft), the thickness itself of the wing's profile will result in a higher angle of deflection of the upper surface, in respect to the lower one. Thus, the speed of the air flow will become even higher on the upper surface, creating a resulting amount of negative pressure (suction generated by the upper surface) much greater than the amount of positive pressure created by the lower surface. As a consequence, the upper surface of a wing profile contributes more to the lift than the lower one.



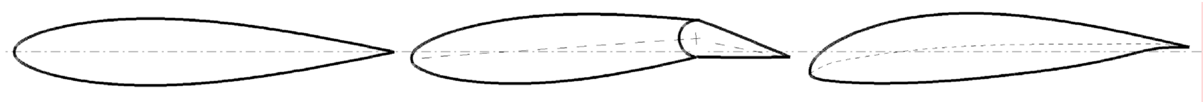
The accelleration of the diverted mass of air depends on the airspeed and the angle of incidence of the lifting area, because with higher airspeed and / or higher angle of incidence more air will be diverted. At a constant angle of incidence, the lift is proportional to the square of the airspeed. If the airspeed is increased by a factor of 1.41, so is the lift; then the angle of incidence of the flying aircraft (even mass) can theoretically be halved. If the airspeed is doubled, only a quarter of the original angle of incidence is theoretically required.
On the other side, the angle of incidence must be proportionally increased with the decrease of the airspeed of the flying aircraft. At constant airspeed, the angle of incidence necessary for the production of adequate lift is inversly proportional to the square of the airspeed factor.
This is valid when the aircraft is flying straight and level. In turns, part of the lift is offset by the inherent component of centrifugal force and a proportional increase in angle of incidence will be necessary.
The Coanda effect on the upper surface will work until a certain positive angle of incidence, depending on wing profile, thickness, air flow rate and surface characteristics. If the angle of incidence is further increased, the air flow will progressively become turbulent and disconnect from the upper surface, creating a drastic increase in drag and a corresponding reduction in lift, since the upper surface of the profile can not anylonger effectively divert the airflow.



DRAG

The production of lift inevitably generates the production of induced resistance, called INDUCED DRAG. With zero lift (vertical dive) the induced drag is zero as well, while in slow flight the induced drag is the major component of the total resistance. This appears quite natural after the previous explanations. Furthermore, all the components of an aircraft (tailplane, rudder, fuselage, wing etc.) generate more drag cause of their shape, position and interference with each other.
This type of resistance is called PARASITIC DRAG (divided in shape (or profile) drag, interference drag and skin friction). All the parts of an aircraft have to be accurately designed to try and avoid parasitic drag, which is at his minimum on the wing. The sum of induced and parasitic drag represents the TOTAL DRAG of a craft.
NOTE: lift can be achieved by setting a symmetric profile at a positive angle of incidence and / or by icreasing the curvature of the profile. The easiest way is to deflect the rear of a symmetric profile, by means of a flap (as already shown in a

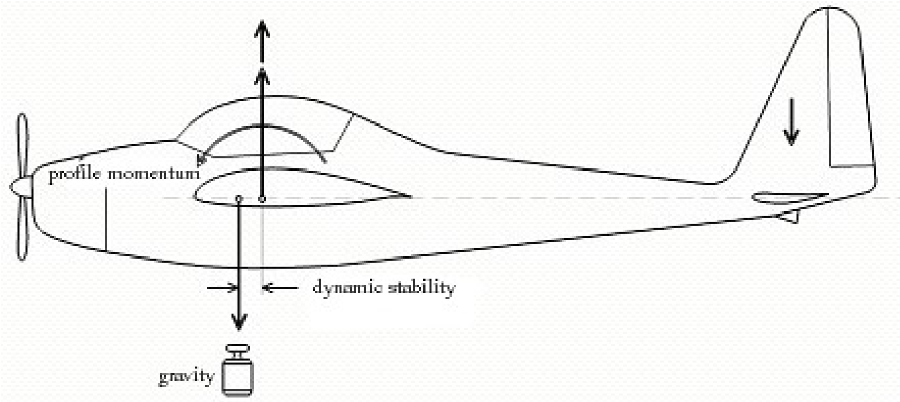
previous illustration). Such "curved" (semi-undercambered) profile, shown in the centre of the illustratio here below, produces already lift at zero angle of incidence (x axis). An enhancement of this effect can be obtained increasing the upper curvature of the profile and smooting the lowering of the rear of it (see right illustration here below). The chord line of a profile (x axis) is normally chosen as a datum line for the angle of incidence. When calculating the coefficient of lift of an airplane, it is fundamental to know the angle of incidence, lift etc. of the wing's profile. Regarding the above-mentioned condition of zero lift, we have to point its importance particularly for cross sections of swept wings: the profile has to be set in a zero lift situation.



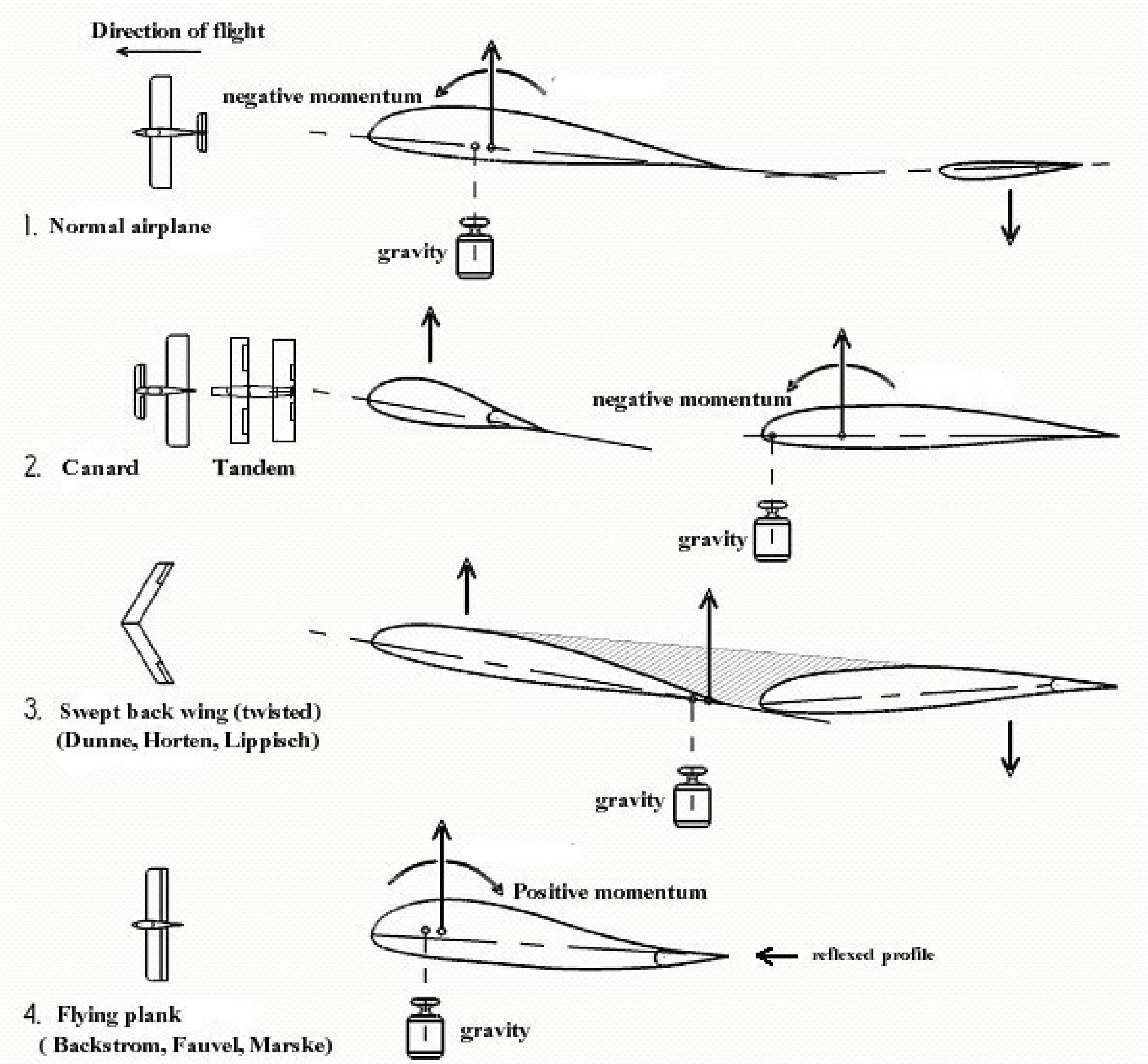
A further effect of the curvature of the profile (right above) becomes important for flying wings. This profile produces a negative momentum, tending to push down the nose of the craft. Some pertinent modifications will be required to bring an aircraft to an automatically stable attitude.

LONGITUDINAL STABILITY

To assure the longitudinal stability, normal aircraft (including canards, tandems and swept back flying wings) must satisfy two conditions:
1) the FRONT LIFTING SURFACE MUST PRODUCE HIGHER LIFT THAN THE REAR ONE.
2) the CENTRE OF GRAVITY MUST BE FORWARD OF THE CENTRE OF LIFT.
If these conditions are reversed, the consequences can be catastrophic. While the pilot will try to correct, the tailplane movable part will deflect to a stall and the aircraft will increase its angle of attack to disastrous levels of instability!
In a normal aircraft, the tailplane is used to counterbalance the negative momentum of the wing profile and to compensate for movements of the centre of gravity (or, in flight, the centre of mass), maintaining it forward of the centre of lift. The tailplane is usually set at a lesser angle of incidence then the one of the wing (DECALAGE), keeping the wing at a certain positive angle of attack to the incoming airflow. Using the stick, the pilot can further control the craft's attitude with the movable part of the tailplane, generating a positive or negative lift momentum transferred through the fuselage, which acts as a long lever.
At the same time, the tailplane produces a corresponding amount of induced drag, which is unavoidable.



Canards (as well as tandems) produce lift with both wings (front canard and rear main wing). The canard, which is set at a higher angle of incidence than the main wing, acts keeping the centre of gravity in front of the centre of lift and also counteracting the negative momentum created by the main wing's profile. The movable part of the canard will move DOWNWARD to increase lift when the pilot PULLS BACK on the stick and viceversa. When the canard exceeds its maximum angle of attack, it will stall (creating a turbulent airflow which will separate form the upper surface) and it will loose its lift. The rear main wing (including ailerons) will not yet have reached its maximum angle of attack, so it will let the nose of the aircraft drop and, after a short dive, the aircraft will resume a balanced attitude. The disadvantage of canards consists mainly in the fact that the front lifting surface (canard) creates a noticeable amount of turbulence affecting the rear lifting surface (wing), increasing the total drag of the craft. The same happens in tandems.



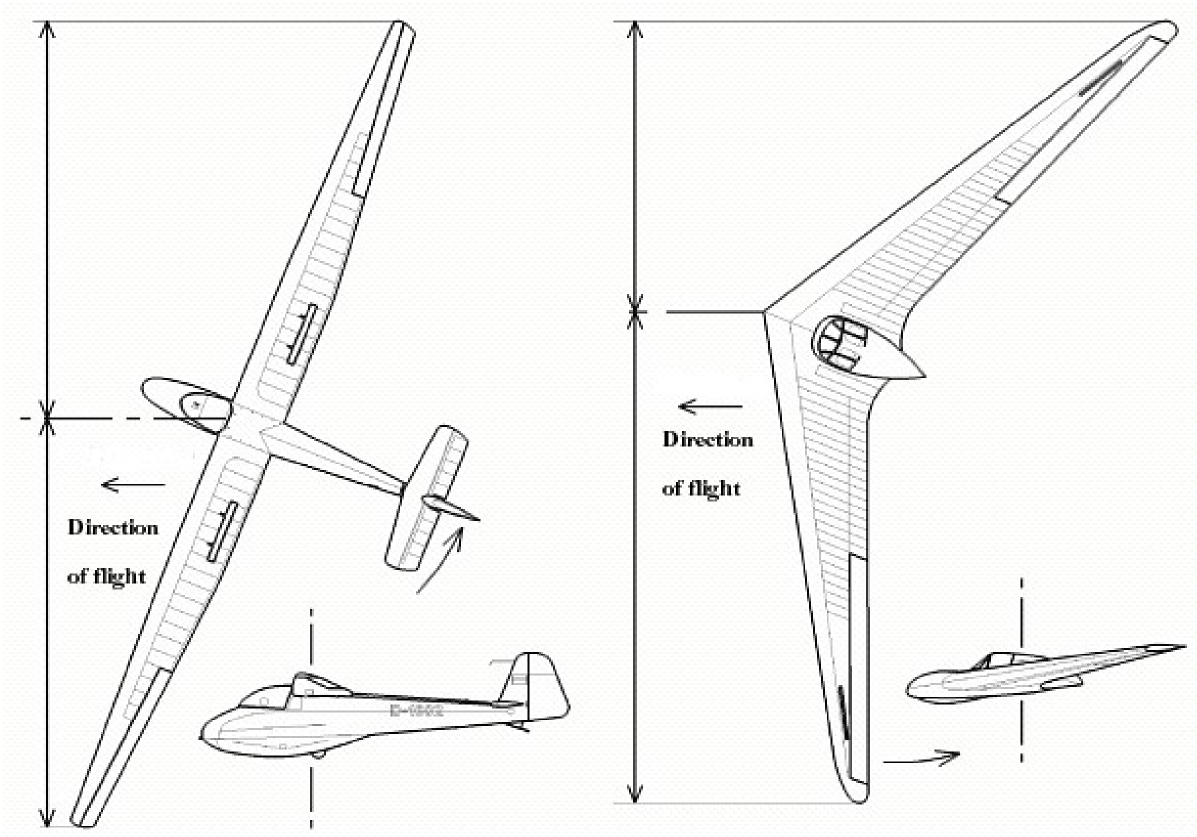
LONGITUDINAL STABILITY IN FLYING WINGS

It is fairly well known that the behaviour of very swept back and twisted flying wings is similar to the one of normal aircraft, because it is in a way a combination of wing and tail in one unit. The outer part of these wings acts as a subtitute for the tail assembly, so that the real lifting area of the wing is somehow reduced. Using a swept back, tapered wing with a symmetric profile or (even better) a reflexed profile, it is possible to eliminate most or all of the wing twist, certainly achieving a higher performance in comparison to the one of a swept back wing with a constant chord and a high amount of twist. The above concept was already successfully applied by Alexander Lippisch, the Horten brothers and other designers during the '30s and eventually refined in the following decades.

Flying planks (unswept flying wings: Backstrom, Fauvel, Marske etc.) have instead very different characteristics. They do not have a front or rear lifting surface. Their chord is their longitudinal limit. To fly in a stable manner and keep the centre of gravity forward of the centre of lift, they need to fly at an acceptable angle of incidence and to do this they use one (or more, when changing profile along the span) of the REFLEXED PROFILES (also called self-stabilizing or S-profiles, referring to their camber line). These profiles were created to substitute, with their rear part, the action of a tailplane. So, while their front part generates positive lift, their rear one (normally from 75% of the chord onwards) produces negative lift. If set at a zero lift angle, they are nearly equivalent to symmetric profiles. When the trailing edge flaps (used as elevator as well) are pulled up by the pilot (stick backward) the reflexed shape will increase and so will the strength of the negative lift (and of course drag). Then the angle of attack of the flying wing will increase and its speed will decrease, with a momentary tendency to a partial stall, which can be unpleasant for an inexperienced pilot, particularly near the ground. Because of their extreme sensitivity to flap-elevator control and of the very small feasible travel of their centre of gravity, unswept flying wings have a fairly limited use. Their advantages, though, are relevant: a really low total drag and a greater flying speed envelope than the one of a normal aircraft. These characteristics lead to much lower power requiremets and considerable fuel economy for the motorized ones.

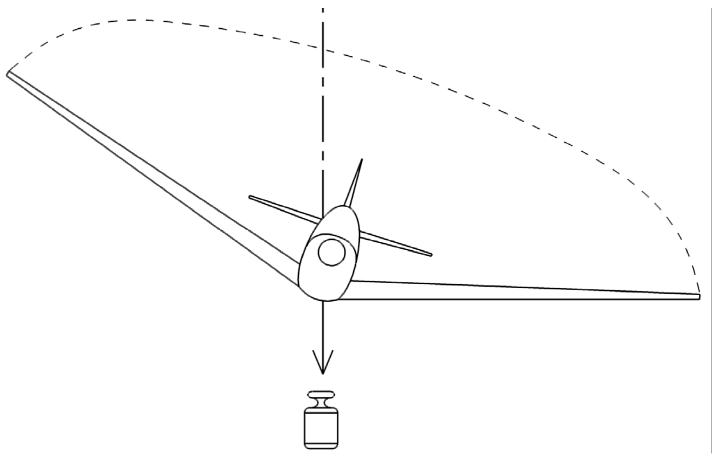
DIRECTIONAL STABILITY

In a normal aircraft, the directional stability is achieved using vertical surfaces (rudder or rudders) positioned after the centre of gravity, usually at the rear of the fuselage.
In swept back flying wings the directional stability is instead obtained by the sweep itself. In the following illustration (left side) it is possible to see that the traditional rear rudder reacts to the airflow and straightens the aircraft, while the back swept flying wing (right side) reacts and straightens because of the different frontal area of each semi-wing in relation to the airflow. Flying planks use instead a fairly big vertical rudder or drag rudders at the wing tips.

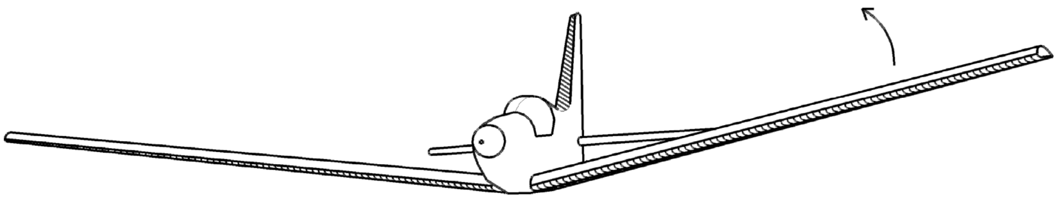


LATERAL STABILITY

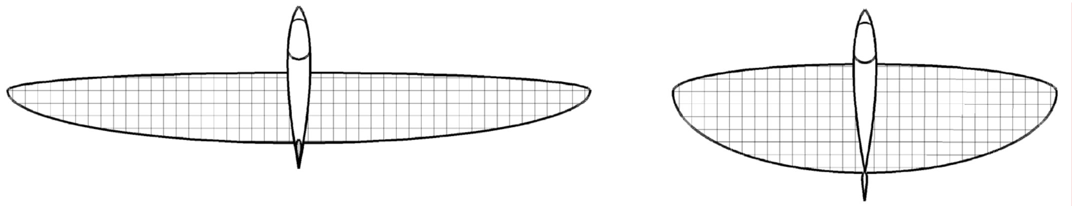
The lateral stability of an aircraft is normally assured by the DIHEDRAL (angle created by the wing tip being higher than the wing root). This configuration produces more lift generated by the lower semi-wing, which presents more effective lifting area and straightens the aircraft back to a neutral position.



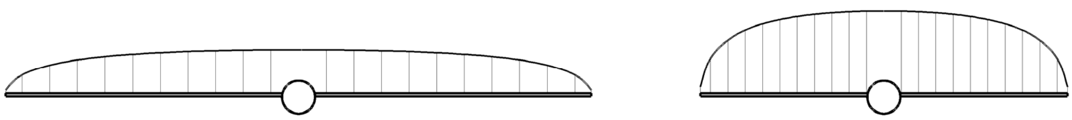
A secondary effect generated by the dihedral is noticeable when YAWING (using the vertical rudder to turn the craft around its vertical axis): the additional lift created by the leading semi-wing will help to re-stabilize the aircraft, bringing it to a smooth, curved flight path after the rudder has been brought back to neutral position.



Back swept flying wings with added dihedral are, as a consequence, theoretically stable on all axis. But unfortunately their reactions are not as precise as the ones of normal aircraft with vertical rudders: they can start to oscillate and reach an overturning point. It is perhaps worth at this stage to explain some of the more common terminology regarding aircraft layout and aerodynamics. To reach the airspeed necessary to fly, an aircraft needs to oppose its total drag by either using an engine or by using its own mass as a mean of propulsion; the latter is achieved establishing a constant attitude to the airflow (gliding flight) by means of elevator setting (two and three axis aircraft) and / or by shifting the centre of gravity forward (weightshift or hybrid aircraft). It also needs to be noticed that the induced drag is lesser if the distribution of lift over the span has an elliptical shape. The following explains how lift distribution can be influenced by several factors. ASPECT RATIO: this term is used to define the ratio between span and (medium) chord of a wing. The illustration below shows, on the left, a high aspect ratio wing and on the right a low aspect ratio wing. Both wings have the same area. It is worth to remember that IN STRAIGHT AND LEVEL FLIGHT, THE LIFT EQUALS THE WEIGHT OF THE AIRCRAFT.



If the two aircraft have the same weight, both wings must create the same lift to keep flying straight and level. But the lift distribution on the higher aspect ratio wing is flatter and it creates less induced drag, while using at the same time a higher air mass (air cilinder diameter = span). In a manner of speaking, the induced drag is lesser if the lift distribution over a wing is flatter, because of the lesser lift (and drag) that the local airfoil needs to generate'

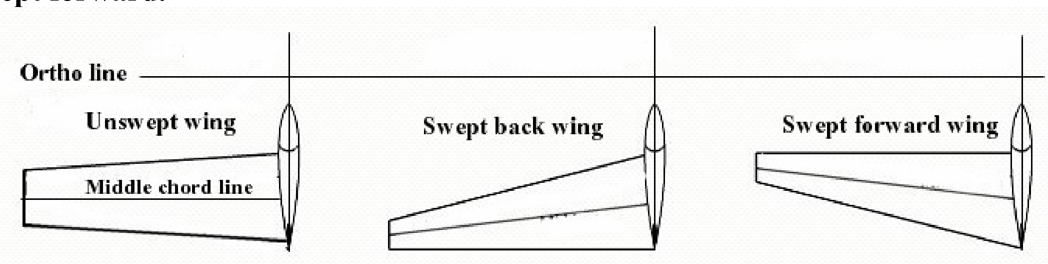


However, a higher aspect ratio wing has problems as well: its structural strength and rigidity must be higher and its chord is smaller then the one of its low aspect ratio counterpart. This means that the airflow separation will happen at a lower angle of incidence and the wing will tend to stall at a lower angle of attack (Reynolds numbers). The lower the aspect ratio, the higher the angle of attack at which a wing can be flown without stalling.

WING GEOMETRY

The shape of a wing is usually compared to geometric figures, such as rectangle, trapezoid, ellipse, circle etc. and this refers conventionally to a semi-wing. If the wing is the combination of more than one shape, it is then compared (always starting from the root) to two or more geometric figures (e.g. tapered or trapezoid, double-tapered etc.). An exception to these definitions is the triangular wing, usually called with the original ancient Greek word (Delta). This method, however, is insufficient to describe more complex wing shapes, so several other definitions will be added.

WING SWEEP: commonly considered as the angle between the leading edge of the wing and the orthogonal to the longitudinal axis of the craft, the geometric sweep is in reality the angle between the middle chord line of the wing (running from the centre of the root chord to the centre of the tip chord) and the orthogonal to the longitudinal axis of the aircraft. In fact, the middle chord line is the resultant of the leading and trailing edge lines (leading edge line + trailing edge line / 2 = middle chord line).
To easily define the type of wing sweep (unswept, swept back, swept forward) it is better to draw, forward of the leading edge, a line orthogonal to the longitudinal axis of the aircraft (Ortho line). When the middle chord line of the wing is parallel to the Ortho line, the wing is unswept (left example below). When the middle chord line of the wing is further away at the tip than at the root from the Ortho line, the wing is swept back (central example below). When instead the middle chord line of the wing is further away at the root than at the tip from the Ortho line, the wing is swept forward.

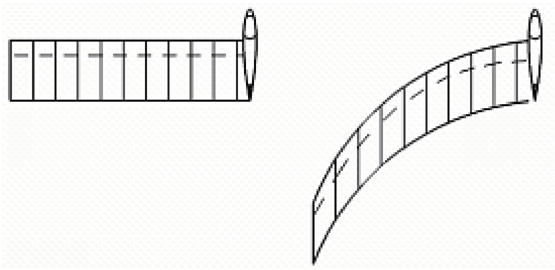


This system works well with simple and compound geometric wing shapes (tapered or trapezoid, rectangular, delta, double-tapered, rectangular with tapered tips).

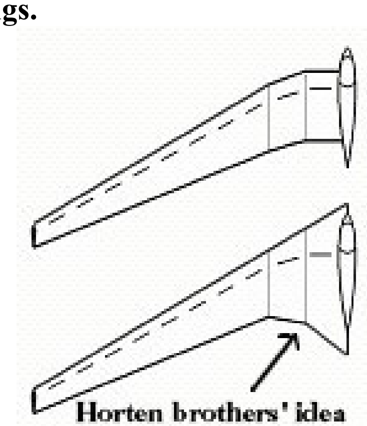
When instead dealing with uncommon or complex geometric wing shapes, it is preferable to use a chord line that joins the 25% of the root chord to the 25% of the tip chord of the wing (quarter chord line or T/4 line), because it is the line on which most of the aerodynamic forces act. In the examples below, it is possible to see that the modified elliptical wing (left) presents a straight T/4 line, so it is technically unswept*. The regular elliptical one (right) presents instead a curved T/4 line, so is swept back.**

*** A famous british fighter monoplane, the Spitfire, employed a modified elliptical wing similar to the one above and had a straight wing spar, proving the point.

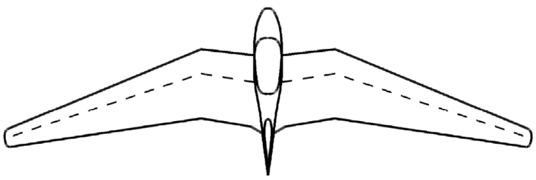
This kind of back sweep is particularly evident in wings presenting a small aspect ratio (for example, circular wings). Another interesting application of this idea is the creation of a "scimitar" shaped wing, starting from a rectangular, unswept one. The quarter chord line is curved to the desired shape and the leading and trailing edges follow it. The spacing between ribs and the wing span remain identical.

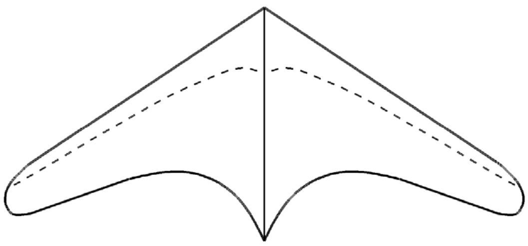


Some designers tried a variant of the idea, creating a sweep, starting at the root of the wing, which weakened the system. The Horten brothers (Germany), instead, created a better solution, keeping the leading edge straight and modifying the leading edge accordingly. As we will see, this is the best way to keep an elliptical lift distribution in swept-back wings.



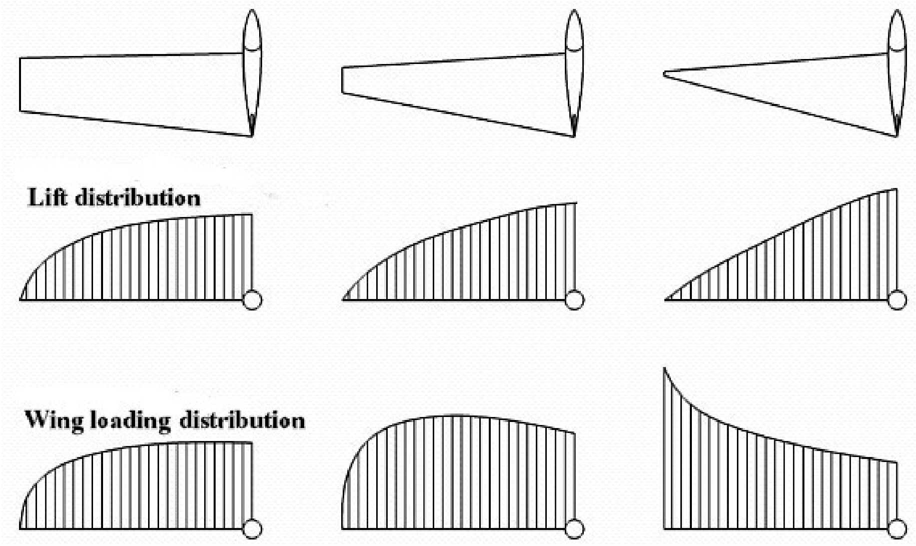
In some cases, as in the SZD6 and in the Horten IX, both forward and back sweep were employed at the same time.



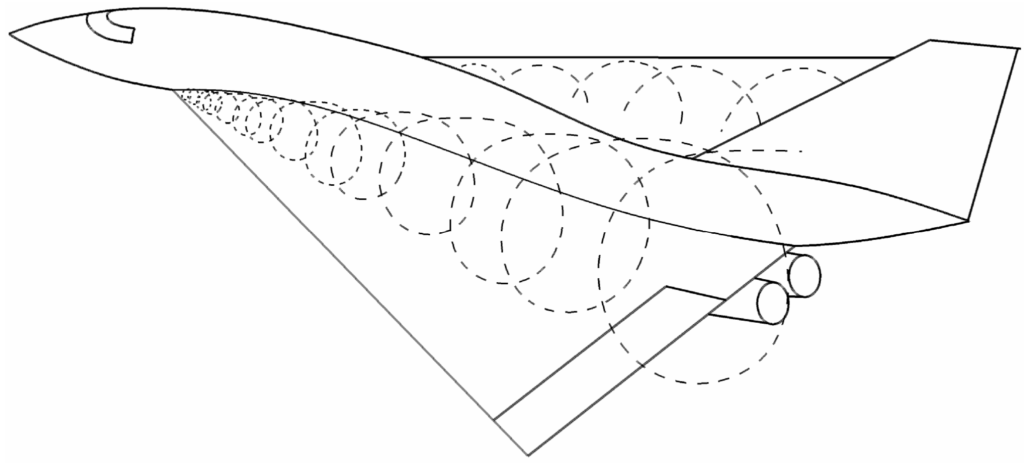


TAPER

The concept of taper is self-explanatory (here below). The three wing patterns (untwisted) have different tapers and the aerodynamic results are evident looking at the graphs.

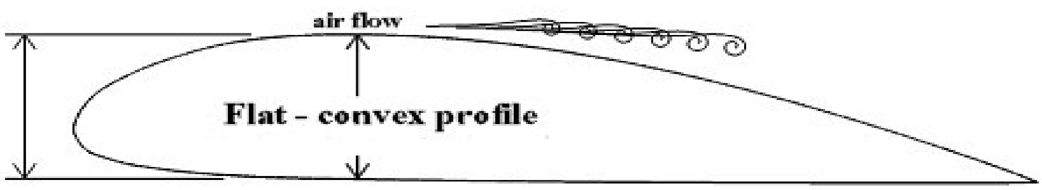


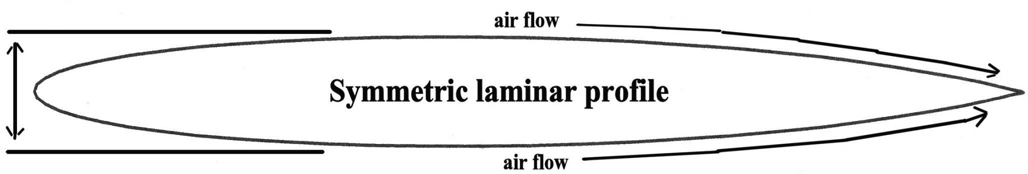
The wing on the left example produces a nearly perfect elliptical lift distribution, which changes to flatter in the central and right examples. It is thus possible to achieve elliptical distribution without an elliptical wing shape. However an increase in taper (central and left examples) will act shifting the wing loading distribution often in an undesirable manner, increasing it towards the wing tip. For a very small or zero tip chord (example on the right) is practically impossible to generate adequate lift (if any!) unless the wing profile can produce an infinitely high coefficient of lift, which is impossible. Such wing shape is critical as well as far as air flow separation in its outer part is concerned.
An exception to the above is represented by delta wings with a very small aspect ratio (1:1 and below) and an extreme taper: an inbound vortex forms at the upper root of the wing (at the beginning of the leading edge) and develops along the upper surface into a conical turbulent flow, producing a strong reduction in pressure and creating a remarcable amount of lift.
Because of this phenomenon, aircraft with these delta wings are stable even when flying at very high angles of attack. In such conditions, the wing profile does not have any remarcable effect. In modern jet-fighters (English Strake) the vortex effect is purposely created by a sharp forward extension of the leading edge along the front of the fuselage, to help during extreme turns.



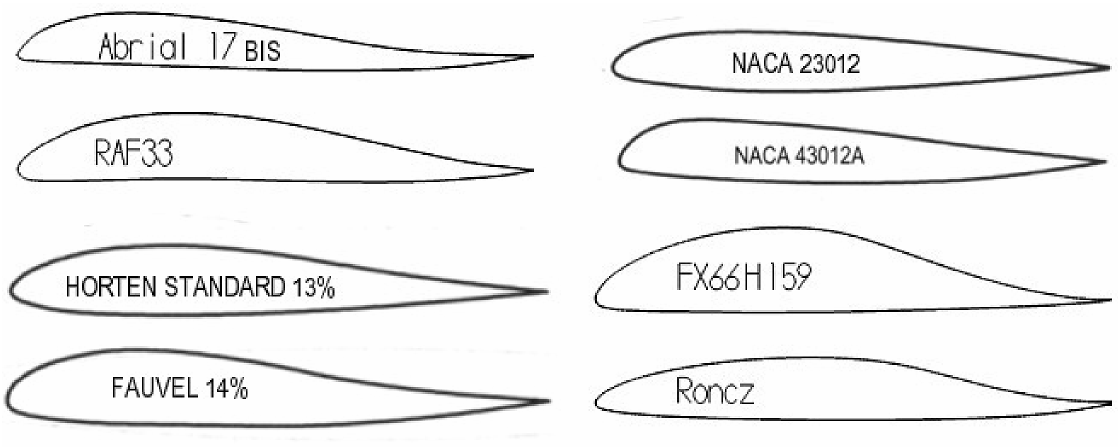
WING PROFILE

Profiles are very important for unswept and little swept wings flying at low speeds and often determine their level of performance and flying characteristic. At the beginning of aviation wing profiles were very primitive, but were soon improved by continuous experimentation and calculations. In the '30s, with the nearly universal adoption of double surfaced airfoils, it became appearent that changing curvature and thickness distribution changed the characteristics of profiles; and that better performance could be reached by setting the maximum thickness back from the leading edge to a point allowing the air flow to follow as much as possible the wing's contour to the rear (initially, at about 25 - 30% of the chord). But with more powerful engines and higher speeds, the air flow began to disconnect even at that point, with a decrease in lift and an increase in drag, both limiting performance. The goal became then to create profiles that could avoid this happening: profiles that had minimum drag and uninterrupted flow (of the boundary layer) above and below the wing. So the LAMINAR profiles were born, presenting a thinner leading edge and a maximum thickness as far back as possible. The first remarcable application was in the wing of the famous P-51 "Mustang" fighter aircraft, which had a laminar asymmetric profile with a maximum thickness of 15.1% at 39% of the root chord line and of 11.4% at 50% of the tip chord line. Since then, laminar profiles have been developed very much further and, together with the appearance and use of composite materials, have contributed to a remarcable increase in aircraft's performance.



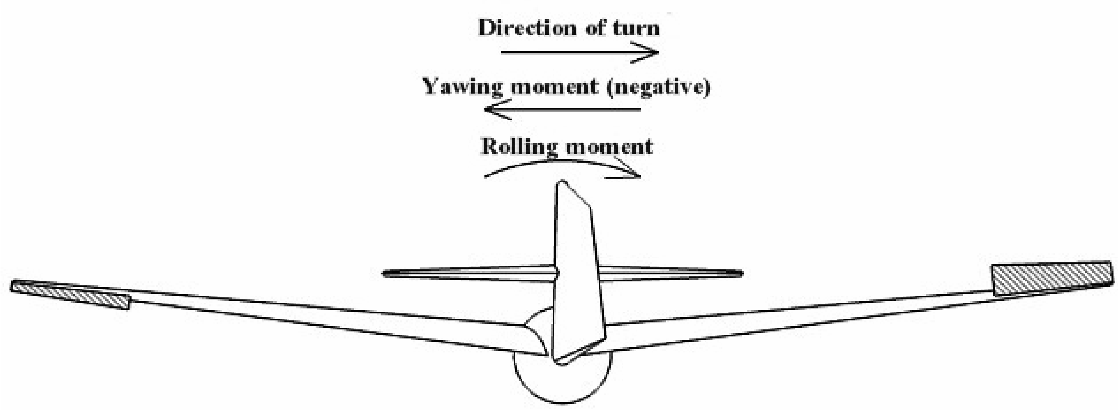


Most flying wing designers are certainly eager to have at their disposal a wide range of suitable laminar profiles, but until now the relatively small interest in this type of aircraft has limited the creation of reflexed laminar profiles, besides those used for rotor blades. Here below there are examples of the most used flying wing profiles.



One of the first profiles purposely designed for flying wings was the Abrial 17 (BIS) (Georger Abrial, France, 1920), used in the A12 glider. Next, the RAF33, created by the Royal Air Force (Great Britain, 1930). The Horten brothers's flying wings (Germany, 1933 'till Argentina, 1994) used very thick reflexed profiles at the root, progressively changing to thin, symmetrical profiles at the tip. Charles Fauvel's profiles (France, 1933 to 1971) derived from G. Abrial's work. They were fundamental to the development of flying wings and were also used by Jim Marske, today's best flying wing glider designer and constructor (U.S., XM1, Pioneer I, Pioneer II, Monarch, Genesis, Pioneer III).
Abrial influenced as well the work of Al Backstrom (U.S. designer, constructor and pilot of the "Flying Plank", 1954) who in turn inspired Jim Marke's early work. The NACA 23012 profile was and is used in flying wings and also in many normal aircraft. It is very interesting, because its S-shaped chord line is extremely mild but very effective. The NACA 43012A is its close relative and has been used, between others, by Jim Markse in his Pioneer II (hybrid profile version) and his very popular Monarch ultralight flying wing. Franz Xaver Wortmann created the FX66-H156 profile, mainly used for helicopter rotor blades but also by Fauvel in his AV48 flying wing. John Roncz (U.S. designer, collaborator of Burt Rutan) created, between many others, the modern profile bearing his name.

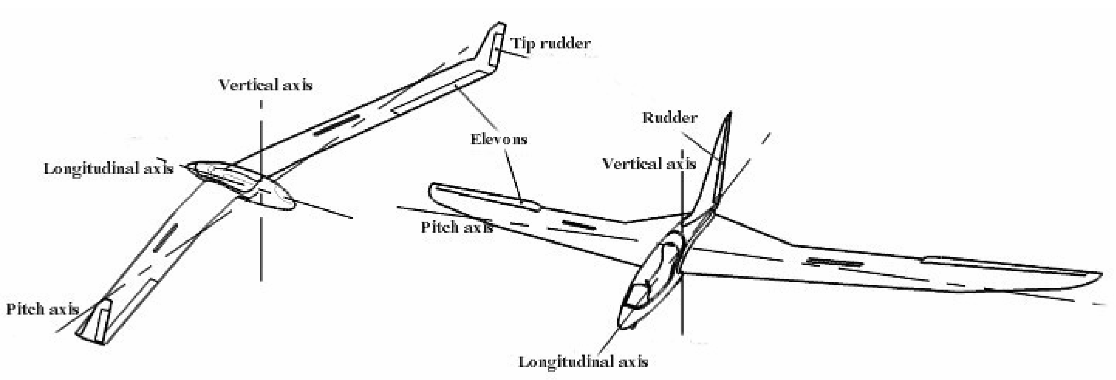
Now, let us learn about the NEGATIVE TURNING MOMENT, one of the worst enemies of aircraft designers. In conventional aircarft coordinated turns are performed by deflecting the ailerons, which induce a rolling moment inclining the aircarft to one or the other side. At the same time, though, the outer wing to the turn creates more lift (and more drag) cause of its higher angle of attack (zero lift condition) and its higher radial speed; the nose of the aircraft then tries to move outwards, against the turn. To correct this negative turning moment a differential movement of the ailerons is required, with the inner aileron to the turn moving upwards to a greater extent than is outer conterpart moving downwards. The turn is further balanced by a positive correction performed with the rudder. When the desired degree of turn is reached, ailerons and rudder are moved back to their neutral position and the elevator is used to stabilize and control the turn. The following illustration shows a rear view of a glider and clarifies this concept.



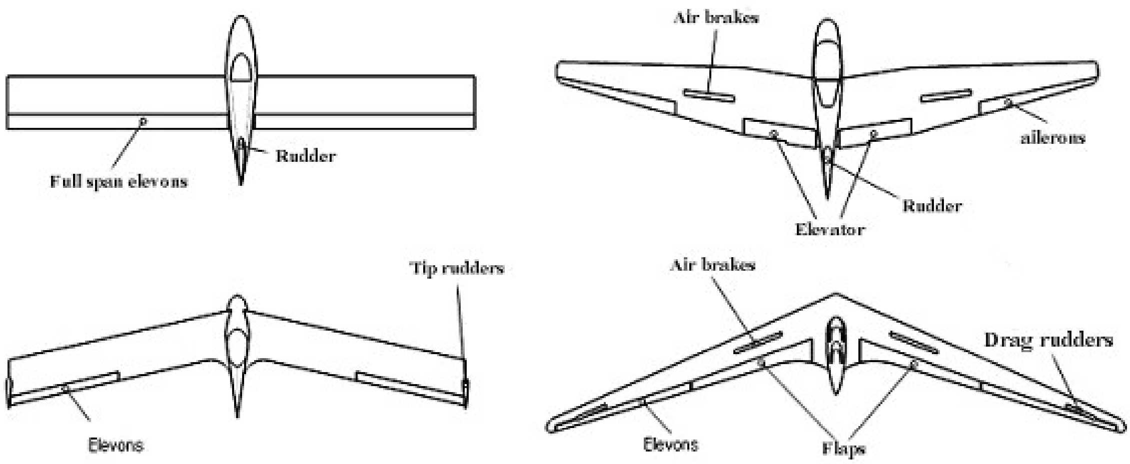
In flying wings the problem becomes more evident because of the shorter arm of leverage created by the limited length of the fuselage, which leads either to the need for a bigger rudder or for a larger rudder deflection (when a rudder is present). The use of differential aileron action would also take effect around the pitch axis at all times, with unwanted consequences. Because of these reasons, control devices that unfortunately increase drag and reduce performance (as roll spoilers or split brake-rudders at the wing tips) have to be employed, in most cases, to achieve safe and coordinated turns.

AIRCRAFT CONTROL SURFACES

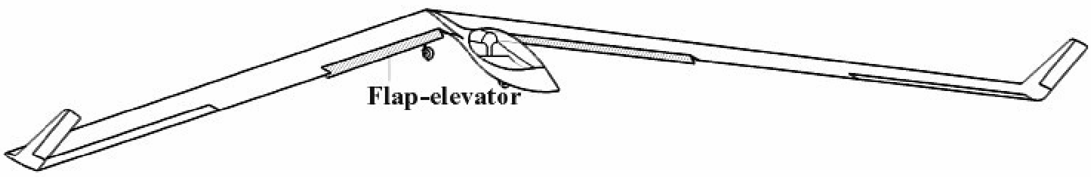
In most conventional aircraft, there are three types of control surfaces: the (vertical) rudder, the elevator and the ailerons. The rudder causes the craft to rotate around its vertical axis (yawing motion) but (with the exception of craft with substantially back-swept wings or a high degree of dihedral) it does not induce a turn. The elevator causes the craft to rotate around its pitch axis (pitching motion), altering the inclination of the flight path. The ailerons cause the craft to rotate around its longitudinal axis (rolling motion), changing the side inclination. In flying wings, elevator and aileron are often combined into one only control surface, called elevon.



The following illustration shows some typical arrangements of the control surfaces used in flying wings of the ’50s.

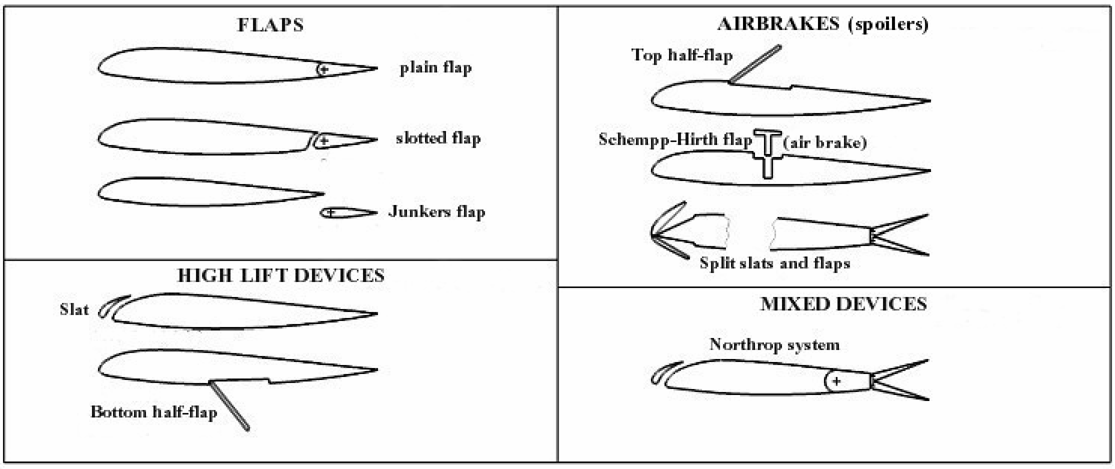


The flying plank on the upper left has only one central rudder, while the swept back flying wing on the lower left presents two tip rudders, which possibly work more efficiently because of the longer arm of leverage. For the same reason, the elevons on this craft can be reduced and do not occupy the full span; the tip rudders could also be normal or split, providing in this case a braking effect on the inner tip to the turn and allowing flatter turns to be performed.
On the upper right, one can see a typical example of swept forward flying wing. The twin elevators are close to the centre of the wing, in spite of a theoretical disadvantage. The ailerons and the rudder are conventional, while there could be two additional rudders (not displayed in the illustration) at the trailing edge of the wing tips. The air brakes, which insure a slower and shorter landing, are conventional as well.
The craft on the lower right is a pure flying wing, without any vertical surfaces. The air brakes and the elevons are conventional, while the extremity drag rudders allow for flatter turns. The flaps are reflexed and drawn in, cause of the noticeable back sweep and high aspect ratio of the wing. Their excursion increases the zero-lift angle in the cetral section of the wing, which corresponds to an increase in cross section. This compensates for the negative profile moment which develops at the same time and eliminates any elevator effect when the flaps are adjusted. The modern ultralight gliders Flair 30 and Swift have very large, neutral flaps. They are used to change the camber of the profile without affecting the angle of incidence of the craft in respect to the horizon, while providing a wider airspeed envelope.With a swept-back flying wing of very high aspect ratio (very limited chord) a flap system working in a manner similar to a canard could be theoretically used. This hypotesis is shown in the following illustration.



This flap-elevator is set well forward of the centre of gravity, which is represented by the pilot's cockpit. When the pilot pulls on the stick, the flap-elevator deflects downward, increasing the angle of incidence of the centre of the sweep and creating lift ahead of the centre of gravity. Unfortunately, this ideal flying wing would lack torsional rigidity even if built with today's most advanced materials; in addition, the effect of the sweep would reduce the efficiency of the above system.

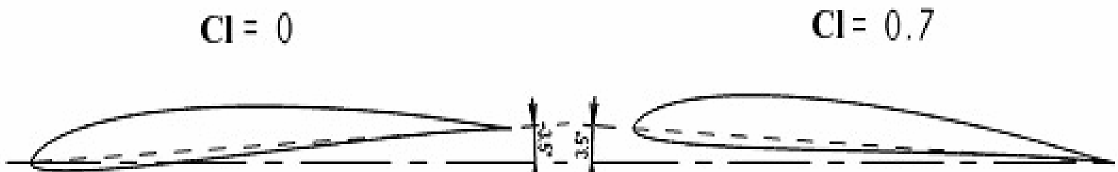
Here below it is possible to see most of the flap and slat arrangements common to flying wings.



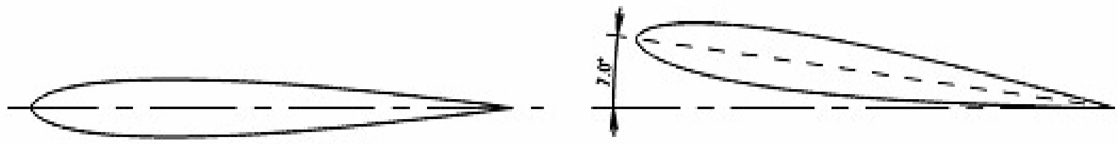
The plain flap (left above) are used in flying wings as elevator, aileron and elevon surfaces. The slotted flap and especially the Junkers flap increase the coefficient of lift by channeling air through the gap (external airfoil flap system). Both types will also produce a little more drag than plain flaps. If used in swept-back flying wings they will work well; in planks or swept forward wings they can improve the stalling characteristics of the craft when positioned as elevons on the outer part of the wing. The following two high lift devices (left below) can instead be used will all wings. The slat, either fixed or retractable, increases the wing's chord and energizes the boundary leyel, allowing stable flight at very high angles of attack. The bottom half-flap increses lift in a moderate manner but drag in a major one. If shifted towards the rear of the chord, its performance would improve but it would not anylonger be torque-free and it would create a downward pitching moment.
The airbrakes (or spoilers) are used as landing aids with conventional gliders. In flying wings they are mainly employed as tip rudders, decelerating the inner wing to the turn. The top half-flap and the Schempp-Hirth flap increase drag and decrease lift, while split slats and flaps strongly increases drag only. The top half-flap can also be used as partial aileron (roll spoiler) and is often positioned slightly more rearword, particularly in modern cargo aircraft and airliners.
The Northrop system, used at the wing tips of the N9M and of the XB 35/49 is a combination of all functions and, although considered unusual and futuristic when created, has proven itself to be valid and still current nowadays. The main flap acts as elevator/elevon, the split rear of it can be used either as an airbrake (both sides opened) and/or as a turning spoiler (one side opened).

SPECIFIC PROBLEMS OF FLYING WINGS.

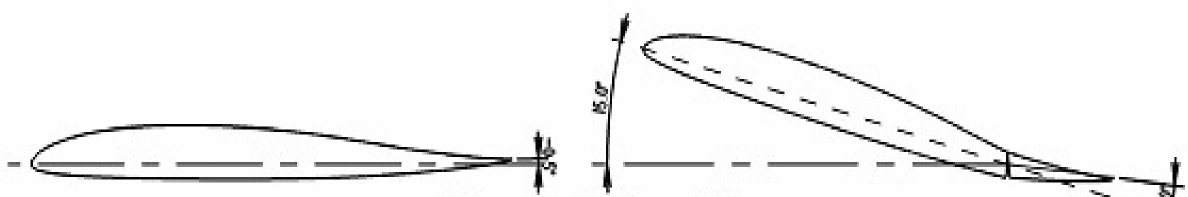
The illustrations here below shows three different profiles (conventional flat convex, symmetric and reflexed (S-profile).
Let us start with at a normal rectangular wing with a conventional profile in a conventional aircraft. Set at a negative angle of incidence (upper left) the wing will not produce lift and dive, with a positive one (upper right) the wing will tend to produce lift and fly. The angle of incidence of the two upper profiles is controlled by the aircraft's tail.
If the trailing edge of the wing is hinged and raised (by means of a flap) the positive angle of incidence will increase. This type of wing profile is called reflexed (or S-profile) and is commonly used in flying wings. In unswept flying wings, an excessive increase of reflex will reduce the zero lift angle and require the craft to fly at a higher angle of attack to reach the same amount of coefficient of lift as a normal aircraft, with the added risk of stalling and tumbling. This would normally restrict their speed range, but Jim Marske (XM-1, Pioneer series, Monarch) has found, with a deep and rewarding analisys and creation of appropriate and efficient wing profiles, a solution to this problem. His flying wings are capable of a speed range equal and even superior to the one of most gliders.



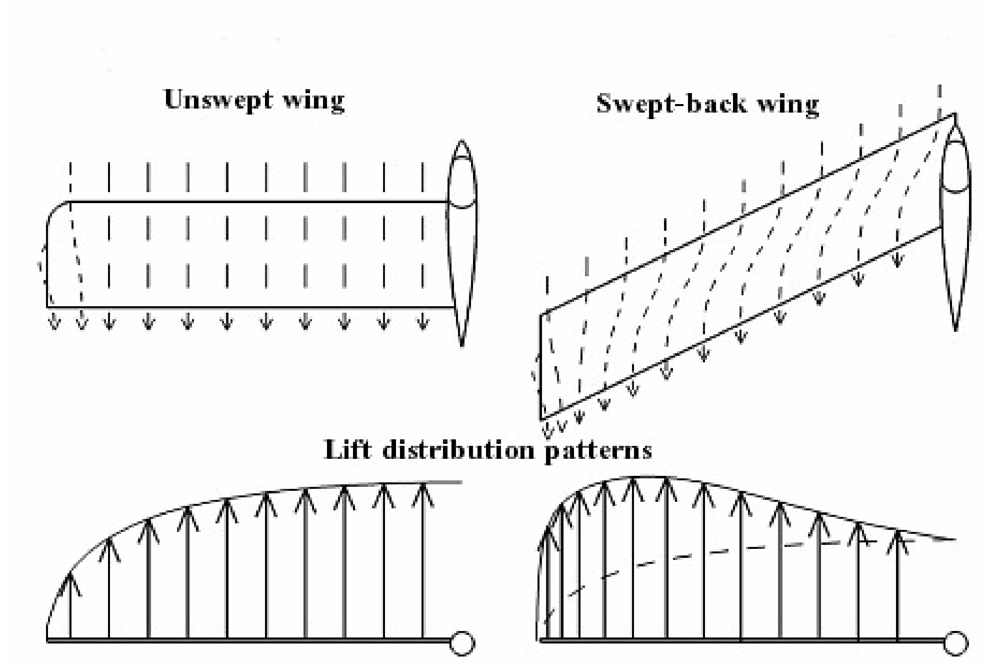
Conventional profile (flat-convex)



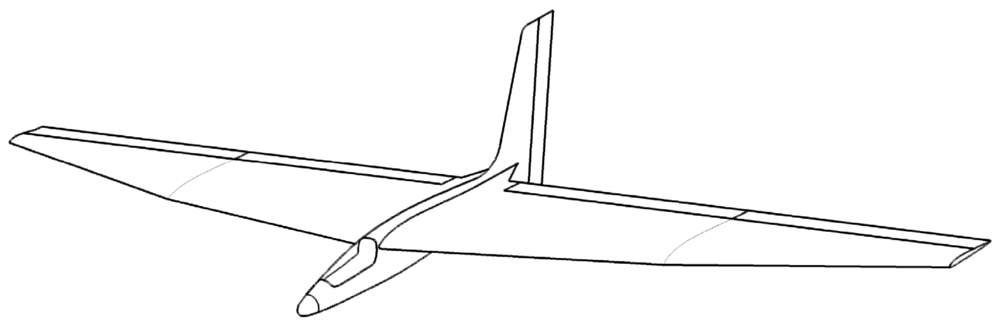
Symmetric profile


Reflexed profile (S-profile)

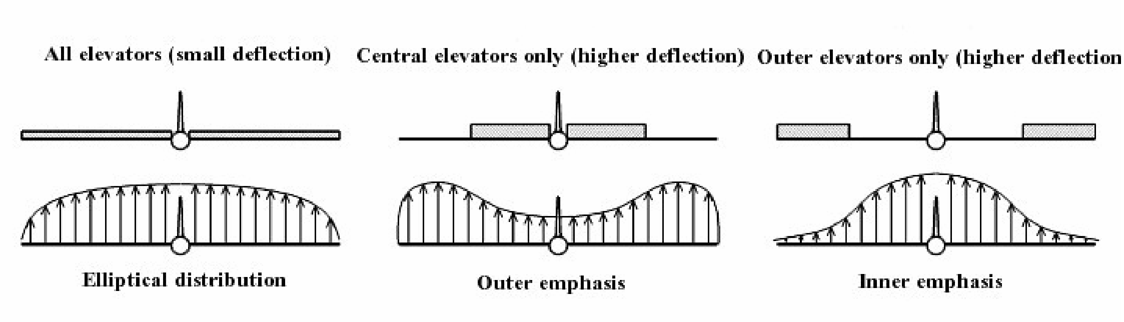
It would be logical to assume, at this stage, that a swept-back flying wing would have a better lift distribution, cause of the more efficient arm of leverage of the control surfaces. In fact, the aerodynamic shape of a swept-back wing deforms the lift distribution as approximatively shown in the illustration below (right).



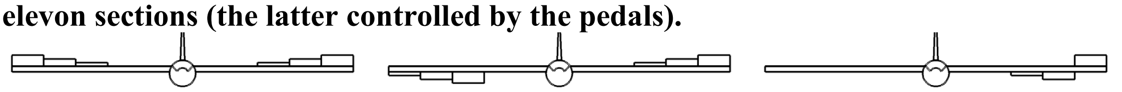
The unswept rectangular wing on the left has a very efficient elliptical lift distribution, while the swept-back wing on the right presents a partial lack of lift at its root and an abundance at its tip. A common remedy to this situation consists in twisting the wing. In this case, though, the swept-back wing will create less lift than its unswept counterpart and will have to fly at a higher angle of attack to be balanced; in addition, it presents a higher aerodynamic load on its outer part, with a similar result to the one described in the previous "TAPER" section.
Several of the early flying wing designers could not come to terms with the position of the centre of gravity on swept-back wings. Many assumed that the craft would be nose-heavy if CG was in the usual position, close to the central front section of the wing. To try and eliminate this problem, some of them decided to place the CG much more rearword, often with catastrophic consequences. Still on this subject, we will look now at the arrangements of different control surfaces.
As already mentioned, <u>an elliptical lift distribution generates the smallest amount of induced drag</u>. In flying wings the elliptical lift distribution is only possible without the use of elevators and/or elevons. The deflection of these surfaces (with the exception of full span elevons) will normally change the lift distribution pattern. The illustration here below shows a flying wing with four horizontal control surfaces. All of them have the same span and area.



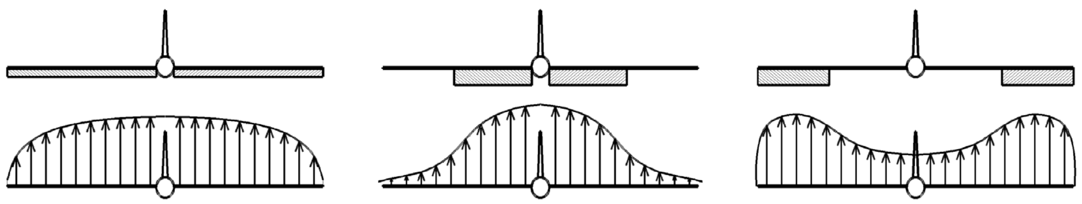
While the original lift distribution is elliptical, let us see what happens when the pilot uses the different controls either together or in pairs.



In the example on the left, all the horizontal control surfaces are used as elevators, at the same small angle of deflection. The lift distribution remains elliptical but the stalling characteristics worsen. In the central example, only the internal elevators are used, at a slightly higher angle of deflection. The lift distribution changes, increasing on the outer section and lessening on the central one. This leads to an increase in induced drag and a decrease in flying speed, with a definite tendency to wing tip stall. The example on the right shows instead that only the outer elevators are used, at an even higher angle of deflection cause of aerodynamic reasons. The induced drag will increase but without severe consequences. The positive note is that the lift is maximized in the centre and minimized at the tips, being equivalent to an hypotetical wing twist; this will lead to good flying characteristics at slow speed.
If the outer surfaces are instead used when turning as differential elevons, they have as well a positive auxiliary effect in counteracting the negative turning moment or even reversing it. If the pilot lightly pulls on the stick and at the same time shifts it to one side to induce a turn, the elevons will move in a differential manner (ideally, the inner to the turn will deflect upwards and the outer will remain almost flat).
This action could be better controlled by creating a three axis control system based exclusively on horizontal surfaces, using the combined function of three different elevon sections (the latter controlled by the pedals).



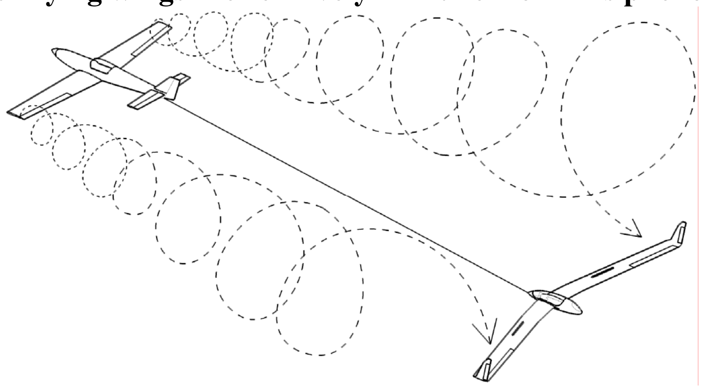
<u>Many of the unpleasant and dangerous attitudes of early flying wings can be related to the inner elevator control (see above).</u>
In the illustration below we are again looking at a flying wing in which the CG is positioned too far back (tail –heavy).



The pilot will generally react pushing the stick forward, to increase speed and keep the craft straight and level. But the wing will then loose stability (reflex, simil-twist etc.) and the elevator will become extremely sensitive. The central and right sketches here above show how the loading will increase and create flow separation at the elevator (local stall due to higher coefficient of lift in the control surface area) with dangerous consequences, especially for swept-back wings: the combined effect of sweep and down-elevator often bring to an uncontrollable forward tumbling.

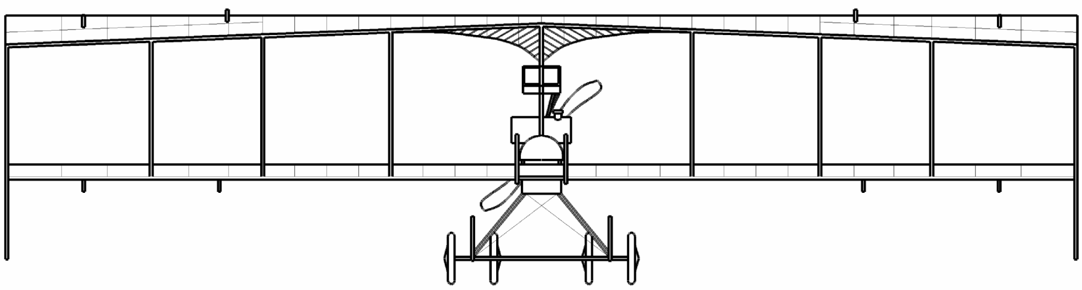
<u>Most flying wing accidents have happened because of the incorrect position of the CG (too far back)</u>, as in the cases of Rudolph Opitz with the DFS40 and of Robert and Kronfeld with the GAL56 (Kronfeld met his death).

We have previously explained that a non-reflexed profile can be used in swept-back flying wings, as long as the wing is twisted. The wing, although, must be rigid enough to maintain the same angle of twist under any circumstance, because if the torsional moment created by the elevons or by perturbances changes that angle, the craft will react as a conventional airplane which is missing its tailplane! An other consequence of this effect is often felt by hang gliders and flying wing gliders under tow, when the vortexes created by the towing aircraft and by its propeller arrive to the towed craft: the turbulence will induce different angles of attack in various areas of the wing, creating unwanted (and often uncontrollable) pitching and rolling moments. The same is happening to slope gliders when flying very near the hill's surface. Unswept flying wings are relatively immune from this phenomenon.

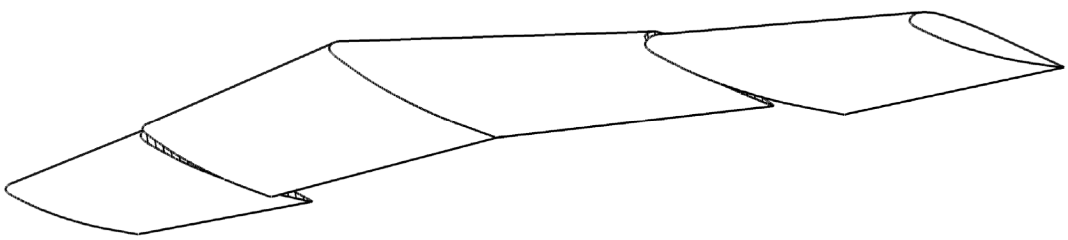


SOLUTIONS TO FLYING WING PROBLEMS

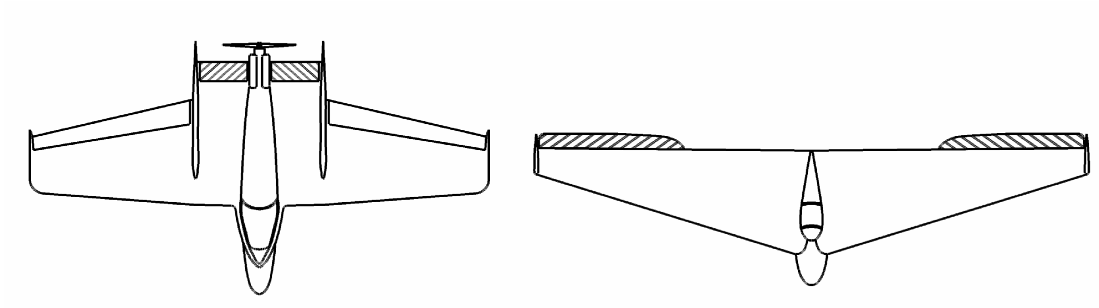
Back-swept flying wings lack adequate lift in their central section and a way to compensate for this lack was already used in 1914 by the English pioneer William Dunne, who increased the angle of incidence in the central section.



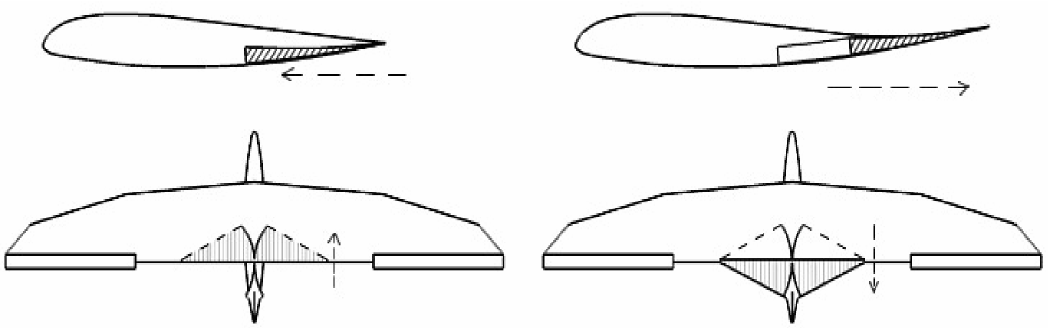
It is feasible to say that any lift distribution pattern can be created by appropriately twisting the wing or by using several horizontal control surfaces, indipendent from each other, set along its span. An other possibility is to increase or decrease the depth of the wing (chord length). The "golden rule" for lift distribution is:" What is unbalanced can be locally balanced by using different angles of incidence and/or changes in chord" and viceversa. The following image could be a resultant:



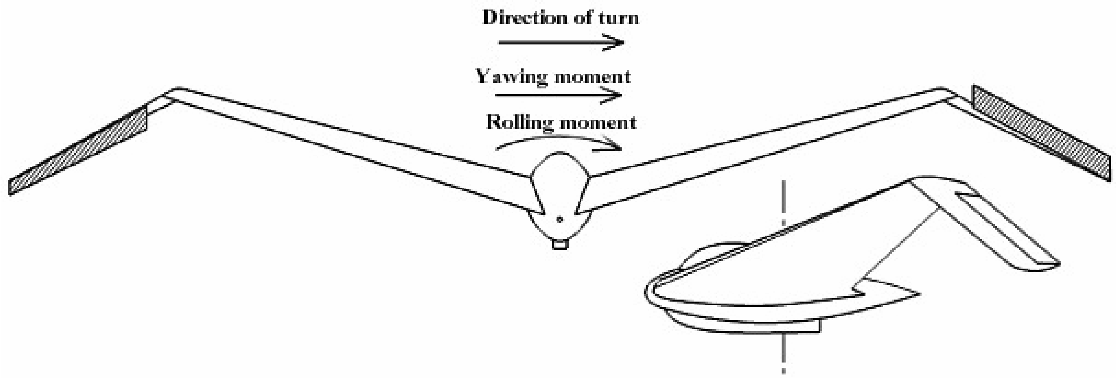
The smaller angle of incidence of the outer part of the wing is balanced by the lengthening of the local chord. The lift distribution nearly corresponds to the one of an untwisted wing, with the lift loading very reduced towards the tips.
Wings which employ several horizontal surfaces and / or very reflexed profiles are generally more aerodynamically efficient than twiste wings with conventional profiles. The lift distribution can also be controlled by locally altering the length of the chord or the thickness of the profile / profiles. The following illustration shows, on the left, a top view of Hugh Lorimer's "Sgian Dubh" (1998) and, on the right, the Russian flying wing glider Tsagi BP1 (1934). In particular, Lorimer's craft presents an elongated central section, finishing in two flapperons. The use of the controls surfaces does not affect the lift distribution.



In the Tsagi BP1, on the right, the increase in chord counterbalances the effect of the outer elevons (when used as elevator). The lift loading is very reduced on the outer wings, giving a docile behaviour of the craft at low to medium speed and with a low coefficient of lift. With higher speeds, the elevators need to be kept at their original neutral position; if a very reflexed profile was to be used or any degree of down-elevator applied, this would result in a very high increase in induced drag on the outer part of the wing. A proper application of the "golden rule" could lead to the following sliding horizontal control surfaces The advantages would be:
1) An increase in positive profile moment.
2) An increase in local and total wing area.
3) A compensating device for a nose-heavy craft (which is desirable when landing or in critical situations but is lessening performance at altitude.)
4) A balanced stick (no positive effort on part of the pilot).
All this WITHOUT any change in lift distribution: it could be ideal for thermalling flying wing gliders, which could be further controlled by elevons.



Untill now we have not yet considered one particular surface arrangement, which could affect the entire history of flying wings: it concerns anhedral (bent downwards) wingtips, which were used for the first time in the Dunnes monoplanes D6 and D7. This configuration became known as "gull-wing". It gives an interesting theoretical advantage:



Because of their position (behind the centre of gravity) these wing tips create a force around the vertical axis, acting as the rudder in a conventional aircraft and rendering the presence of the latter unnecessary. Unfortunately, this wing tips can be dangerous in unswept flying wing, cause of the evident lack of leverage.

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This detailed presentation of the aerodynamic characteristics of flying wings shows that they definitely are the simplest (and most elegant) form of aircraft. Because of their peculiarities and behaviour (which is different from conventional aircraft) and the amount of compromises that designers have to face when projecting them, it is understandable that only a few successful craft of this type were conceived, built and flown up to now. Let us consider their advantages and disadvantages in comparison to conventional aircraft.

Advantages:

1) Their structural design and construction are more simple.
2) They can be very controllable and easy to fly, while very agile.
3) The absence of redundant parts (fuselage, tail assembly etc.) creates higher efficiency, allowing for less wing loading and smaller coefficients of lift.
4) Reflexed profiles can have a smaller coefficient of drag at low angles of attack.
5) Less power is required to keep them flying.

Disadvantages:

1) To keep good flight characteristics, the lift distribution may not be optimal.
2) The position of the centre of gravity has limited travel.
3) The positioning of pilot, passengers and engine/s is fairly critical.

In conclusion, the author believes that flying wing aircraft will have a definite place in the future of aviation because of their possible advantages. Future aircraft will increase in area and, mainly through military developments, automatic flying control ("fly-by-wire", Northrop B2 and other craft) has become a reality. At the end of the '90s Boeing (Phantom Works), Airbus and Tsagi started to work on the

blended wing-body or BWB concept (see illustration here below). On the 20th of July 2007 Boeing, in collaboration with NASA, flight-tested successfully the X-48B, a radio-controlled scaled model (6 meters in span) of the projected 100 meters wide future BWB craft, capable of transporting up to 1000 passengers. During 31 minutes of flight at a cruise speed of 220 km/h, the model reached an altitude of 2400 meters, giving excellent results. Further development is continuing.
A smaller company, the Florida-based Wingco, produced the "Atlantica" full size prototype. This very elegant craft, meant for the private market, is a five-seat BWB completely built in composites. An unfortunate accident, happened in 2003 during a fast taxi-trial, has slowed (but not ended) its development.