*Newsletter #15*

# Theory and Practice of Using Flying Wings

## Can the tailless airplanes be competitive in model rocket glider contests?

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By Tim Van Milligan

With the introduction of the B2 bomber into the stable of the USAF aircraft, the all wing airplane and gliders are becoming topics of discussion again. The history of the flying wing, as this configuration is most popularly called, goes back into the late 1800's before the Wright brothers got

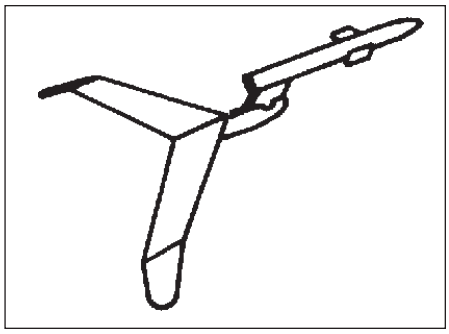

**Figure 1: Estes' *Nighthawk* Glider**

their flyer flying, and since then, they have made several "comebacks" into aeronautic popularity.

The flying wing made its mark on the rocketry world in the 1960's with the Estes release of the "Nighthawk." See Figure 1. This plane has since faded from the memory of most modelers, except a few hard-core modelers, or flying wing freaks. Those that do remember it will recall that it is a true tailless glider. It had a pop-pod on the front end, with small canard like vanes on the pod, that were more visual ornamentation than they were practical. If the model was improperly built, the vanes could be adjusted to straighten the boost of the rocket.

Other Estes' flying wing kits include the Astron Space Plane, and the Astron Invader.

Estes also had a new flying wing kit release for 1993 with the introduction of the "AVR Condor." The AVR Condor has a vertical tail to make the model a little bit more yaw stable, and more importantly, forgiving for young, inexperienced builders. These two small planes on the model are very efficient flyers when properly trimmed, and if used in NAR competition, should be very competitive.

### *Advantages of Flying Wings*

The chief advantage of the flying wing to competition would be its lower drag coefficient. Since a pure flying wing possesses no fuselage and no horizontal tail surface, it may be possible to achieve very low zero-lift drag coefficient. A theoretical improvement of about 40% may be obtained for a given aspect ratio. The benefits all trickle down from this fact: because of the lack of tail surfaces, the glider will have a lower weight, and hence the wing loading will be reduced. Because the wing loading is reduced, the bending moments on the wing will be less, and hence less structure will be needed to maintain wing strength and integrity.

Because of these benefits (lower Cd, lower wing loading), the sink rate will also be reduced; something which all competition modelers aim to achieve. Additionally, depending on how the glider is designed an built, a flying wing can be much more maneuverable than a conventional configuration.

This is why this article was written: to see if the advantages of flying wings can be

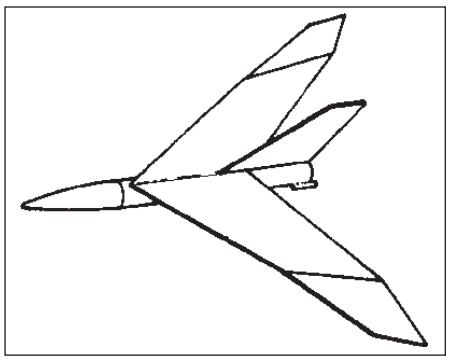

**Figure 2: Estes' *ARV Condor* Glider**

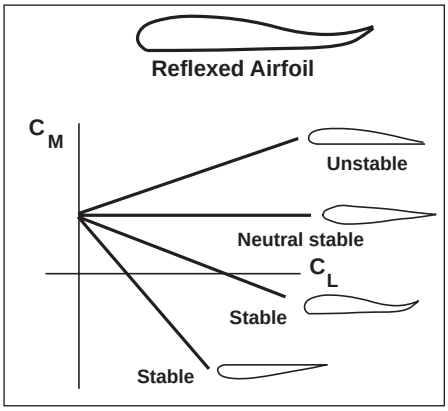


**Figure 3: Airfoil stability chart.**

utilized in competition, particularly on the international level. At this point, it is wise to look at how a flying wing works, and after that, I will attempt to open up a discussion on what is needed to be done to bring flying wings to a competitive level.

### *Stability of Flying Wings*

The flying wing is an exercise in ones ability to master stability. In general, a typical cambered glider wing is unstable, that is, it will not achieve a normal flat glide unless it is rebalanced and modified into a flying wing. If you have ever taken a balsa wing and tried to fly it before attaching it to the rest of the glider, you will know that it will just tumble on its own pitch axis.

For any flying wing aircraft, the condition of static stability is simply:

$dC_m/dC_l = X_{c.g.} - X_{a.c.}$; and this must be less than or equal to zero.

This is the same equation given in by Guppy's article (<u>"Calculation of the Neutral Point"</u>, *The Journal of the MIT Rocket Society*, April 1980) but without all the terms relating to the effects tails have on aircraft. The neutral point, or the location of the c.g. with respect to the aerodynamic center (a.c.) is satisfied when $dC_m/dC_l$ is equal to zero. The equation then becomes:

$X_{c.g.} = X_{a.c.}$

This means that the furthest aft that the c.g. can be on a flying wing is directly over the a.c. Anything aft of this point will make the flying wing aerodynamically unstable.

This doesn't tell us much about the design of flying wings, except to keep the CG ahead of the a.c. for stable flight. But even this condition alone does not mean the wing will achieve a stable glide.

Going back to the original assumption that $dC_m/dC_l < 0$ for stability. This is really based upon $dC_m/dC_a < 0$. Here "a" (angle-of-attack) is used in place of Cl because of the direct relationship between the two at low values of a and $C_l$. Therefore our stability equation now means that the moments acting about the pitching axis with respect to changes of angle-of-attack must be less than zero. It should be noted here that positive moments are those that tend to pitch the nose of the aircraft upward; so for positive STABILITY, we want negative (nose heavy) producing moments.

The aerodynamic pitching moment (M) is formed by the resultant air force on the wing ($R_w$) and its fore-and-aft distance (x) from the center-of-gravity. Then:

$$dM/da = - d(Rw \bullet x)/da$$
$$= -(x \bullet dRw/da + Rw \bullet dx/da)$$

The negative sign comes from our definition of stability.

Assuming all the moments are acting at the a.c., the x=0 and the equation becomes:

$$dM/da = Rw \bullet dx/da$$

This means that stability depends upon the sign of dx/da and margin of stability on its magnitude, since the resultant air force cannot change its sign. Now dx/da is the travel of the center-of-pressure for the wing system being considered. When dx/da moves forward (in the negative direction) the system becomes unstable.

Our criteria for static stability of a flying wing means that dx/da > 0 for positive static stability.

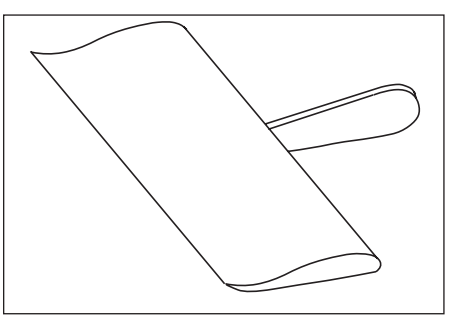

**Figure 4: The "Flying Plank."**

As most of know, high lift on wings is produced with positive cambered airfoils. However, all positive cambered airfoils the center-of-pressure moves forward when the angle of incidence increases. In equation form this would be stated: dx/da < 0

With this type of airfoil, it is necessary to provide a tail (either in back or in front) to counteract the unstabilizing moments originated by the air force on wing. For flying wings having cambered airfoils, the stabilizing action of a tail plane has to be replaced by aerodynamic means; i.e. the "tail" is incorporated directly into the wing system.

It should be noted that a airfoil section where dx/da = 0 can be used if some sort of gravity stabilized (pendulum) system is used. The airfoil that meets this requirement is the symmetrical airfoil, or the flat plate.

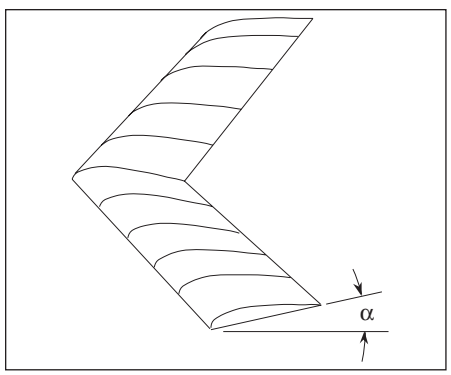


**Figure 4A: Washout on a swept wing provides inherent stability.**

There are two solutions that can be used to fulfill the requirement of dx/da > 0. The first is the *Flying-Plank* category embodying airfoil sections of positive stability, i.e. an airfoil having heavily reflexed-camber sections all along the span. The second is a moderate swept back plan shape with washout at the tips.

A reflexed airfoil is one where the trailing edge has been turned upward. A look at a graph showing the $C_m$ vs. $C_l$ (or "a") shows why a reflexed airfoil will work See Figure 3. A reflex airfoil gives a stable center-of-pressure travel over the whole useful range of incidences. The invert, simply-cambered airfoil (also shown in the graph) is the limit for such stable airfoil sections.

Tailless aircraft employing this type of airfoil can be made to resemble a straight plank (a flying wing with zero sweep back), as many models have proved using this method. See Figure 4. The bent-up trailing edge (reflexed airfoil) is what makes "flying planks" stable . On this type of glider (see *Popular Science* magazine, May 1991, page 9) a weighted boom must be added to the front of the glider so that the center of gravity is ahead of the aerodynamic center. This would satisfy the first condition of a stable airfoil section.

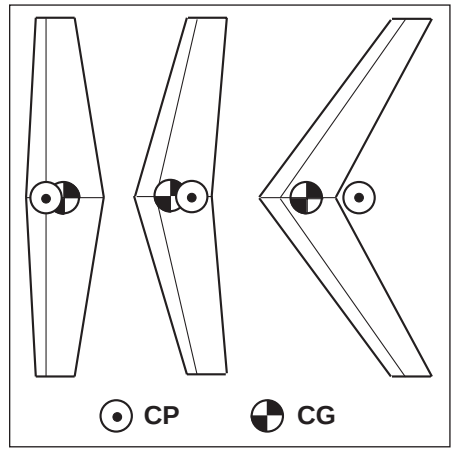


**Figure 5: Aft movement of CP with an increase in the sweep angle.**

A drawback of reflexed airfoils is there performance qualities. Their main deficiency is that they suffer from low values for the maximum lift coefficient. This is an inherent deficiency, since the reflexed tail portion is intended to balance the lift produced by the front part of the airfoil. Static stability cannot be gained without the loss of lift. A loss of maximum lift will be in the range of 9-15%. The benefit of reflexed airfoils is in their lower minimum profile drag, although the gains are very modest, somewhere around 5%.

Unstable wing sections can always be made stable - as the conventional airplane (with tail) shows. This is where the idea of sweepback and washout came from. This was proved mathematically in 1906, so the idea is not new. But in order for this system to secure static stability and balance over the whole range of useful incidences, large degrees of sweep-back and washout are required.

Sweep allows the aerodynamic center to be moved reward so that the center of gravity is ahead of it, and the washout provides a positive pitch moment. The CG of the aircraft can be moved fore or aft by the angle of sweep. See Figure 5.

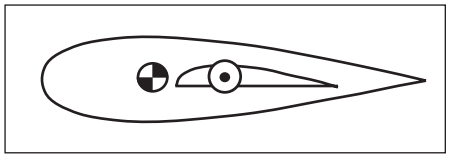

**Figure 6: Adding a fuselage moves the CG forward on tailless aircraft.**

A disadvantage of swept wings is that they have an inherent tendency to stall prematurely at the tips. This is associated with the lateral flow (outward flow toward the tips) of the boundary layer. A benefit of the washout is that is lowers the angle-of-attack of the tips, decreasing the tendency of tip stalling at high angles of attack.

Flying wings that rely solely on the wing planform shape for stability are disadvantaged. Weight and performance are degraded. The drag is high and the maximum lift is low. Structurally, the wing is bound to be heavier. Most likely, this type of flying wing will be inferior to conventional type airplanes. Sweep with washout shouldn't be discounted entirely though, as the loss of mass (dismissing the tail) may be of more importance than flying qualities, particularly when the differences might be small.

A compromise between the low maximum lift, stable airfoil sections, and the higher drag, stable wing shapes, is to use changes in airfoil sections across the span. If done properly, this provides aerodynamic wash-out, reducing the need for drag producing geometrical wash-out. This should lower the drag of flying wings.

Another compromise would be to use moderate sweepback with washout, combined with the use of stable airfoil sections. Here again, the airfoil need not be constant across the entire span of the wing, but could use a combination of reflexed and symmetrical airfoil cross sections.

Adding a fuselage to the tailless glider also gives the designer more latitude in positioning the aircraft CG. It will add additional drag, but it may be worth it. See Figure 6. On swept forward or oblique wing planforms, the fuselage may be the only way to move the CG far enough forward to make the aircraft stable. See Figure 7. On RC aircraft, a fuselage may be necessary to house the radio gear and servos on thin wing birds.

One thing that is inherent on all flying wings is their sensitivity (in pitch) to changes in control surface movement. This is because of the short length of the aircraft. This may not be a concern on free flight gliders, but on RC planes, this is something to watch out for. But this may not be all too bad, because this sensitivity leads to increased maneuverability.

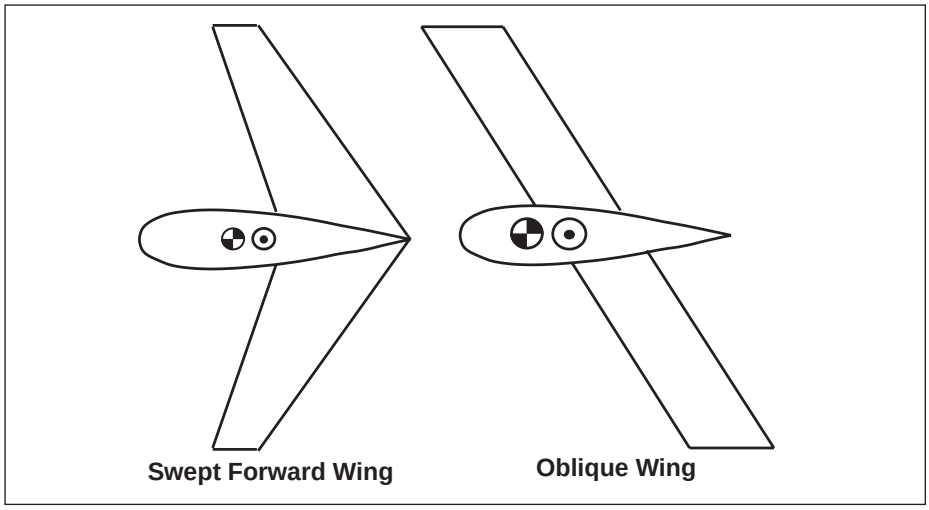


**Figure 7: Adding a fuselage may be the only way to achieve proper CP-CG relationships for non-typical configuration aircraft.**

### *Lateral Stability*

The above discussion hopefully will help you understand a little bit better the longitudinal stability of a tailless aircraft. But it takes more than longitudinal stability to make a successful aircraft; you also need yaw and roll stability.

The roll axis on a flying wing is controlled similarly to conventional type aircraft. This is usually done with adding dihedral to the wing. See Figure 8. A few of the references mentioned using 5° of dihedral on wings with no sweep. See Geoffrey A. Landis' article and the one by Bob Parks for additional information on dihedral and roll stability (see references listed at the end of this article). Sweeping the wings also adds roll stability, and if a swept wing is used, the dihedral is reduced or even eliminated. Both of the articles mentioned above cover this aeronautic occurrence.

Another way to add roll stability to any aircraft is to lower the center-of-gravity. This will require mounting the wing high on the fuselage, or by hanging a pod below the wing. See Figure 9.

Yaw stability on a flying wing aircraft is harder to achieve, unless a vertical tail is added. Adding a vertical tail is the simplest way to add yaw stability, if you don't mind the added drag an extra appendage will create. "Purests" hate the idea of a vertical tail, but they are effective, particularly as an interim control method while the design is being developed and "trimmed."

If a vertical is being added, it is best to place it as far aft as possible, so that there is a large moment arm to the center-of-gravity, for the forces to act. Sweeping the tail aft adds to this moment arm, as does putting the tail at the tips on swept wing configurations. See Figure 10. Use planforms of higher aspect ratios on the verticals to cut down on the induced drag, and so that the tips of the tails are out of the relatively thick boundary layer.

For vertical tails placed on the wing tips, pay close attention to both fins, so they each produce the same amount of drag and that they both have equal masses. The drag produced on the tips acts with a far larger

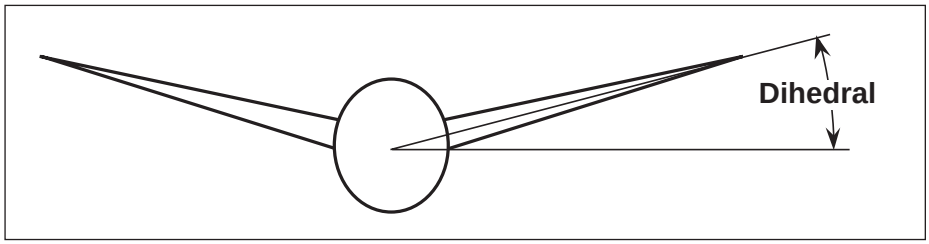


**Figure 8: Adding dihedral to an aircraft increase roll stability.**

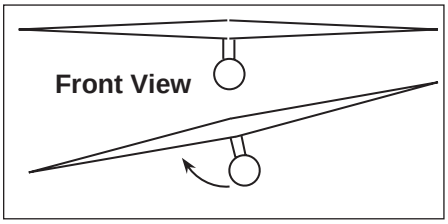


**Figure 9: Mass positioned below a wing provides "pendulum" stability.**

moment arm, and any imbalanced produced by these could really throw the aircraft out of trim.

Adding the vertical tails to the tips and giving them some initial "toe-in"also increases the ability of the flying wing to "weathercock" into the wind (back to the intended direction of flight). See Figure 11. Toe-in uses drag on the vertical fin to

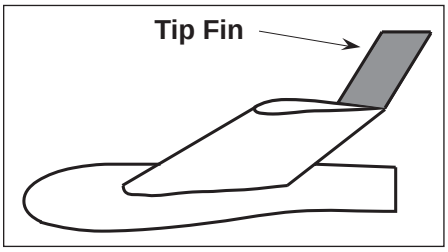


**Figure 10: You should position tip fins as far aft as possible to increase their effectiveness.**

turn the glider to a position of least resistance, which would be directly into the wind (although with the wind might occur in rarer instances). To illustrate this concept, when glider experiences some yaw, the wing that is forward presents more of its profile to the wind, and thus creates a lot of drag. The opposite fin on the trailing wing is now at a lower angle of attack, and thus its drag is lower. The resulting force imbalance creates a moment about the center-of-gravity that turns the glider back into the wind. See Figure 12.

On report suggest that one use "toe-out" on fins of high aspect ratio (see references written by Charles J. Donlan). The reasoning would be that the high aspect ratio fins generate more lift than drag, so the trailing fin (in a yaw) would have a larger lift force than the leading fin (whose angle-of-attack is lower, and possible negative). See Figure 13. These two theories: toe-in vs. toe-out, can be debated by the reader, but I personally lean toward toe-in because drag is so much easier to produce than nice clean lift.

The direction of "toe" can be set by either physically mounting the vertical fin at an angle relative to the direction of flight, or by sanding some camber into the fin. For instance, to produce "toe-in" you would sand the fin so that the convex side if toward the center of the glider. See Figure 14.

Yaw stability can also be obtained on swept wing configurations with negative dihedral. Negative dihedral doesn't have to be across the entire span of the aircraft, it could be just at the tips. This increases the inherent directional stability possessed by a wing, since they act like lower surface tip fins — directional stability is manifested through the outward lift developed on the wing tips. See Figure 15. One must realize that negative dihedral doesn't help the roll stability of the aircraft, so the gains made in yaw stability must be balanced against the losses in roll stability.

This leads to "diffuser tip" wings. These wings were first discovered and used by early aviation pioneers after studying the wings of soaring birds. A "diffuser tip" wing is one where the tip is bent downward, and at the same time is tilted forward. See Figure 16. Comparing this to what was previously presented in this article, it can be surmised that the downward tilt is for yaw stability, and that the tilting forward is a form of washout (for longitudinal stability). Because of the washout, the diffuser tip is mostly used on wings with some degree of sweep.

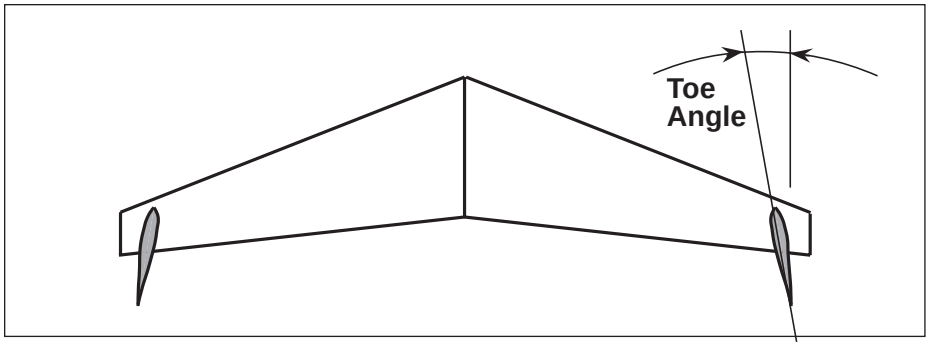


**Figure 11: Vertical fin "Toe-in" on wing can provide some yaw stability.**

The diffuser tip offers several advantages which makes them very popular for flying wings. As already mentioned, they give yaw stability and pitch stability. If they are used, the vertical tail can be made smaller or eliminated all together. They also act like "toed-in" vertical fins (by producing drag), so they also help with keeping the aircraft on its intended course (weathercock stability). Of course, aerodynamically the diffuser tip is an element,

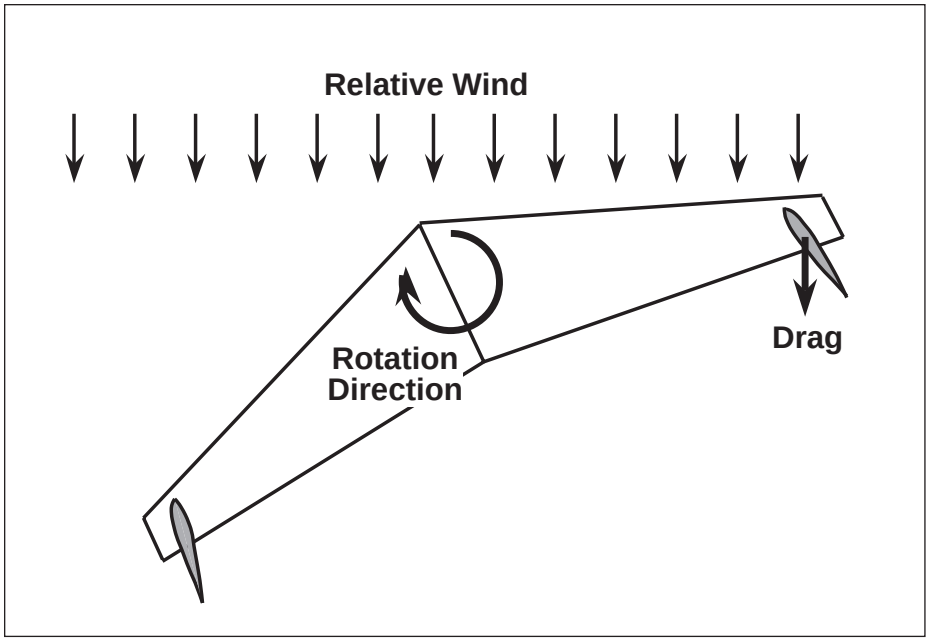


**Figure 12: Drag on "toed-in" vertical fins result in a way restoring force.**

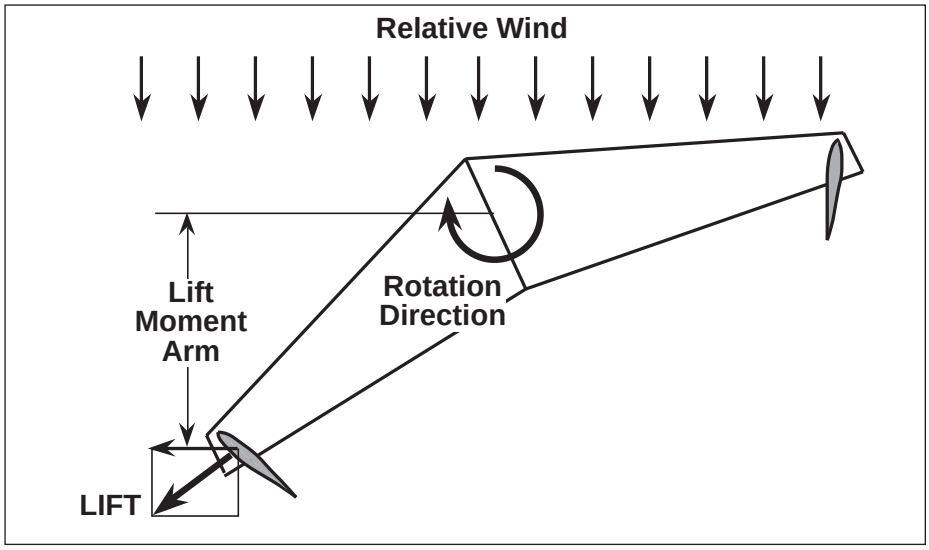


**Figure 13: Lift on "toed-out" vertical fins also result in a yaw restoring force.**

which by itself causes drag and down lift. But since it can take the place of fins and rudders, and also that of wing twist, the deficiency in performance caused by it, can be considered tolerable.

### *Control Surfaces*

Control surfaces on gliders are used to change its orientation, or to set it into some initial trim condition. Ailerons are used on the flying wing to control roll, just as they would on a conventional aircraft. Another way to affect roll is to use spoilers to destroy lift on one wing. The resultant imbalance will roll the aircraft in that direction.

Pitch and yaw are controlled differently since a flying wing has no tail; the effects of rudder and elevator must be incorporated into the wing.

If the wing has vertical fins, a rudder is easily added, although if they are on the tips, control linkage for RC control, may be slightly complicated. When the wing doesn't have a vertical fin, yaw control can be accomplished by "split flat drag rudders." These are flaps on the tips that split along the long side, so that it deflects both upward and downward at the same time. See Figure 17. These rudders will also cause a rolling moment because a the lift imbalances on the wing, so opposite aileron will a have to be added if the flight is to remain level.

Controlling yaw on a flying wing starts with a good design that keeps all unbalanced yaw forces low, and has some inherent yaw stability. Then usually, only small yaw corrections will be needed.

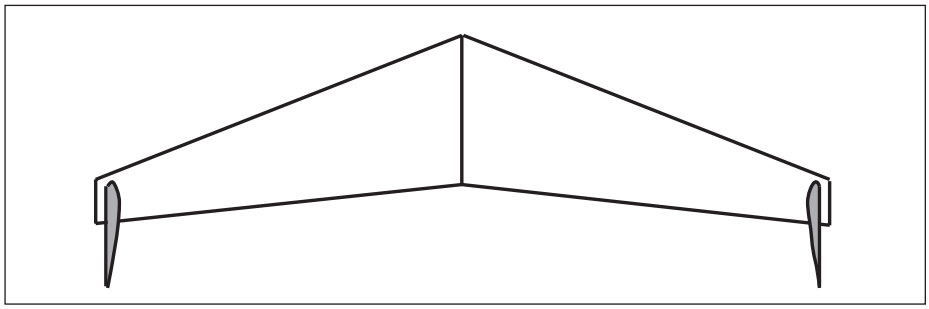

**Figure 14: Aerodynamic "toe-in" from airfoiled vertical fins.**

Pitch is on flying wings are controlled with the outboard flaps, with both wing flaps operating together in synchronized up and down movement. See Figure 18. Since the flaps can also be used for roll control, they would be properly termed "elevons." On RC planes, this is done with a mixer, either mechanically in the aircraft, or electronically at the transmitter.

Since the balance requirements for flying wings are more severe than for conventional aircraft, the elevator of a flying wing usually must be deflected considerably more than that of a conventional airplane. This would be a comparison of aircraft of the same static margin in order to produce the same changes in trim lift coefficient in flight. This large deflection will have to be taken into account while designing the flying wing, because if you want to apply elevator at the same time with aileron, the deflection of the flaps will have to be even greater (if elevons are used to combine control functions). The total effective deflection range for an elevon must be the sum of the ranges required for the aileron and elevator. See Figure 19.

Pitch can also be controlled by sliding a mass back and forth along the aircraft's centerline. This relatively simple method for controlling pitch, when the model is correctly balanced, is a result of the relative short range of CG travel available in most flying wings. Note: if a mechanical mixer (sliding tray) is used in the flying wing, that the direction of travel be watched, as it may affect the pitch of the aircraft, as just noted.

### *B2 Bomber Control Surfaces*

It is interesting in light of the discussion of tailless aircraft to look at the U.S. Air Force's B2 bomber, affectionately known as the "stealth bomber." See Figure 20. The facts about this bomber I gleaned from old issues of *Aviation Week & Space Technology*.

"Most of the complex notched trailing edge of the wing is fitted with large control surfaces. The outboard wing controls are divided into inner and outer surfaces that move independently. The outboard surfaces, call "split rudders" or "drag rudders," have upper and lower surfaces that move independently." These split rudders can also be used as air brakes when oper-

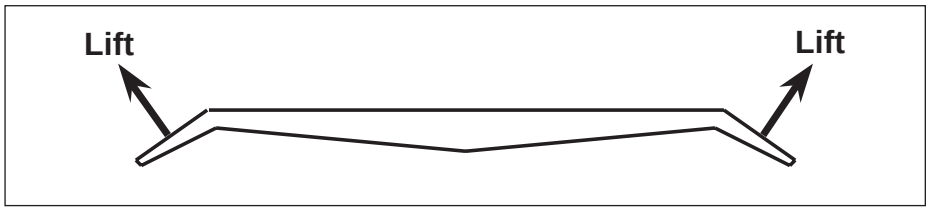


**Figure 15: Directional stability increased with downward drooping wing tips.**

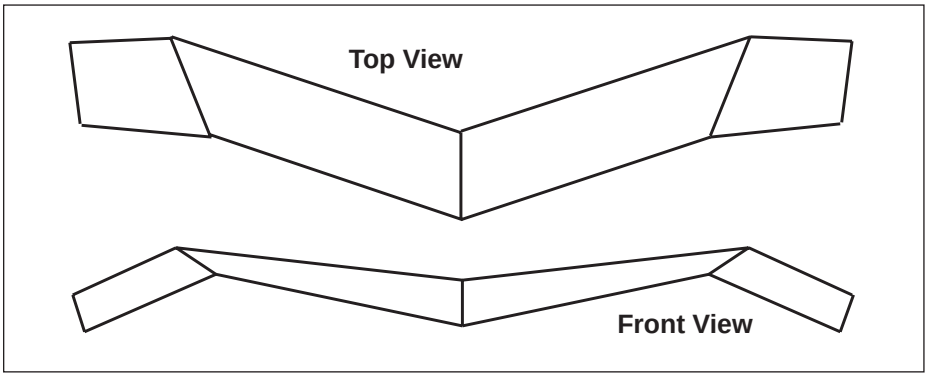


**Figure 16: Diffuser tip flying wing; similar to the old Estes *Nighthawk.***

ated simultaneously.

The inner outboard trailing edge control surface is a elevon.

The next trailing edge section toward the center has equally large control surfaces that also seem to divide into inner and outer sections. These are two more elevons, mechanically separate for redundancy, but moving in synchronization with the outboard elevons.

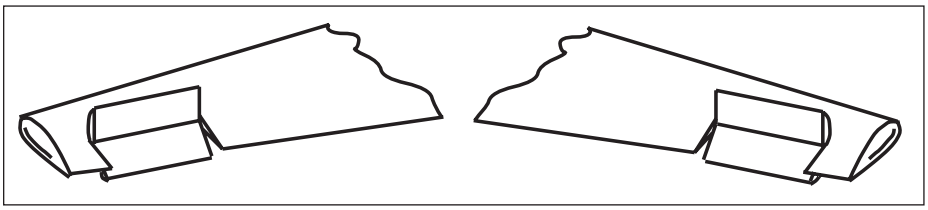

**Figure 17: Split-flap drag rudders to control yaw on RC tailless aircraft.**

The trailing edge surface downstream of the engine exhaust is non-moveable. Probably because of heat problems associated with the engine.

The "beavertail" surface at the aft end of the centerbody is movable, and is likely to be used for pitch trim, and "to optimize the span loading of the aircraft for lower drag."

According to the July 31, 1989 article in *Aviation Week*, the drag rudders are biased open during all phases of flight. They seem to think that the "drag does not increase substantially during the first part of control deflection, so the surfaces are biased open for rapid aircraft response."

## Suitability of Flying Wings in Competition

Will the flying wing bring an improvement in performance in competition? Since there has been little information on people who have used them in the past, there is nothing to substantiate a hard opinion. It will probably take some additional testing by experimenters to show a trend one way or another. One particular area of questioning that must be answered is: what are the characteristics of flying wings during the boost phase of the flight? If the boost characteristics are bad, how can they be improved, and will these improvements affect the altitude that the rocket will achieve?

In RC competitions where a precision landing is required, a highly maneuverable aircraft may be desired. This may be a good place to try a flying wing glider.

The flying wing type aircraft can offer several advantages in competition, but the jury is still out on their suitability due to a lack of information from past accomplishments.

## Construction

Building flying wings should not require any building techniques or skills that are not already used in model rocketry.

One particular area of construction that is not often used in rocketry, but isn't difficult to create, is "washout" of the wings. Washout of the wing either requires that the wing be warped, or that it be cut and sanded to give proper washout (as in diffuser tip wings). This is really not hard to achieve using balsa wood. Foam core wings should be easier to create the washout, because it can be cut into the cores initially.

Typical flop wings can also be used on flying wings, as they are used on conventional type aircraft. Diffuser tips lend themselves to flop wings, because they already have a hard line, which is just begging to be used for flop wings.

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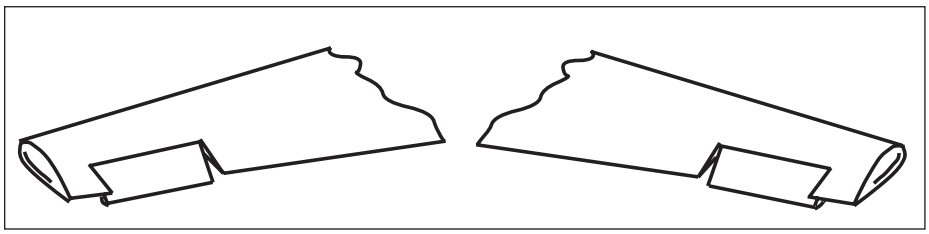

**Figure 18: Pitch controlled with flaps acting in synchronization.**

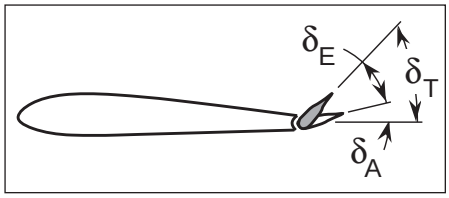


**Figure 19: Deflection of flaps is sum of both elevator and aileron deflections.**

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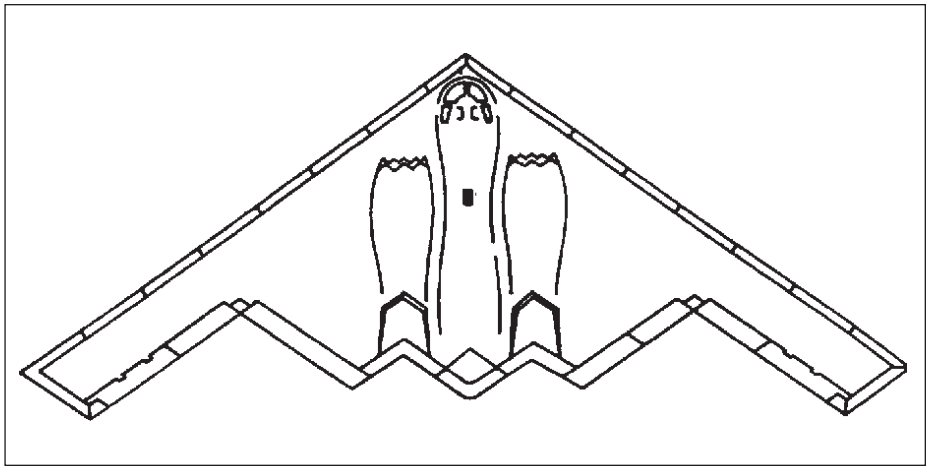

**Figure 20: Control surfaces on the B2 Bomber feature redundant flaps.**


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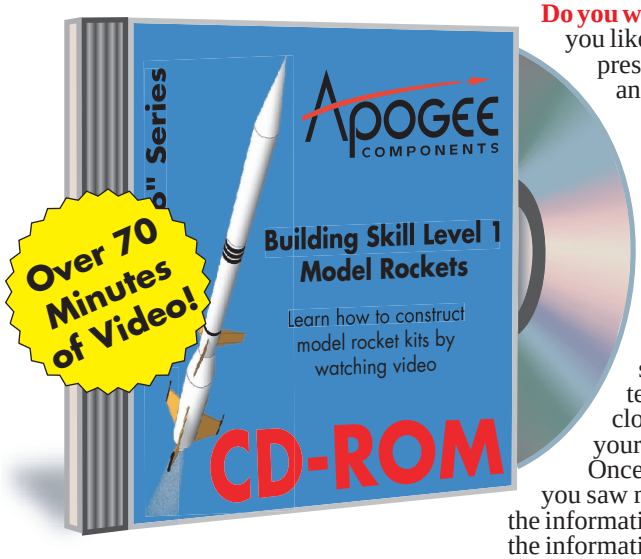


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