# TECHNICAL REPORT

ESTES

TR-4 Boost Gliders

by Thomas E. Beach

I. Introduction

Few sights in model rocketry can match the beauty and grace of a boost glider rocketing swiftly into the air, then returning in a slow, gentle glide to the surface of the earth. Building and flying a successful boost glider is one of the most challenging projects in model aeronautics, and it can be one of the most rewarding.

In this report we will discuss the principles of flight by which gliders operate, as well as the practical aspects of designing, building, and flying boost gliders. Do not be discouraged if some of the concepts in this report are difficult to understand — it is not necessary to fully comprehend the theory of flight in order to build a glider that will awe the spectators as it traces lazy circles in the sky overhead. Even novice rocketeers can successfully fly boost gliders built from Estes kits if they follow the instructions and carefully build and trim the glider. But the more you know about how a boost glider works, the better you will understand the reasoning behind each step, and the greater are your chances of a perfect flight.
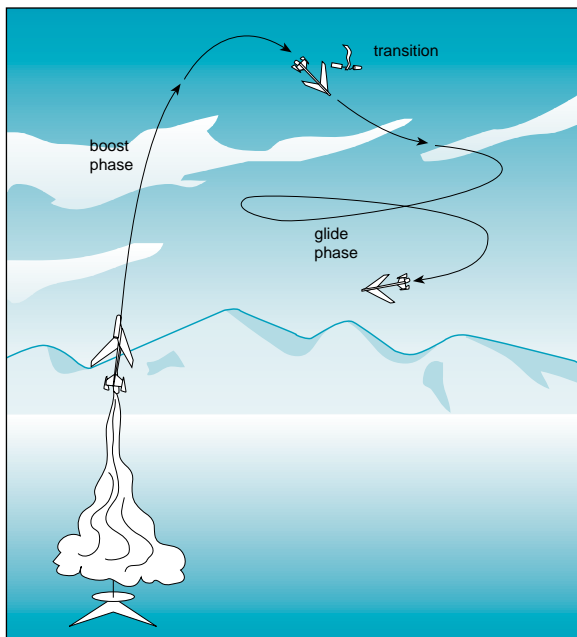

II. Basic Definitions

A *boost glider* is a model rocket that ascends vertically into the air by rocket power, then part or all of the model returns as a glider supported by aerodynamic lifting surfaces. During boost phase the boost glider is a stable, ballistic vehicle just like any model rocket; it must not ascend in a shallow climb using lift from the wings. Near peak altitude the boost glider *transitions* from boost configuration into glide configuration. The transition from rocket into glider is the most basic problem of boost glider design, and modelers have developed many ingenious methods of making the metamorphosis, which are covered in section VI.

Historically, the first boost gliders were essentially model rockets with overly-large fins that could transition into a glide configuration. These *rear-engine* boost gliders were not very efficient as gliders, but at the time it was amazing to get a successful glide recovery to work at all. The original Estes Technical Report TR-4 documented some of these early efforts.

The state of the art of boost glider design took a giant leap forward with the development of the *front-engine* boost glider. Rather than trying to make a rocket that glides back, Larry Renger, a model rocketeer with experience building model airplanes, adapted a conventional glider to boost like a rocket. The early Estes Technical Report TR-7 discussed front-engine gliders. Variations of this front-engine design are still the standard today for high performance free-flight boost gliders.

To make the transition from boost to glide configuration, many boost gliders separate into multiple parts. A special sub-class of boost gliders, called *rocket gliders*, makes the transition without separating or ejecting parts. Rocket gliders are more complex to design and fly.
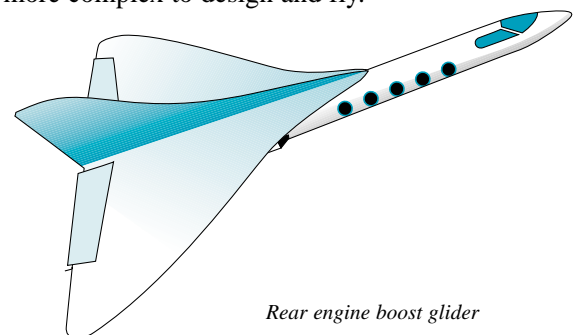
Rear engine boost glider
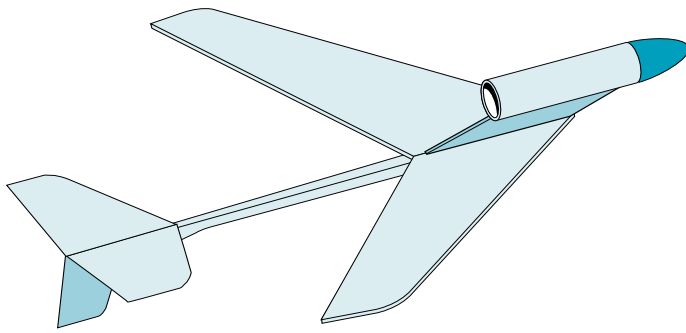
Front engine boost glider

III. How Gliders Fly

In order to understand how boost gliders work, we must first discuss the theory of flight by which all gliding aircraft operate.
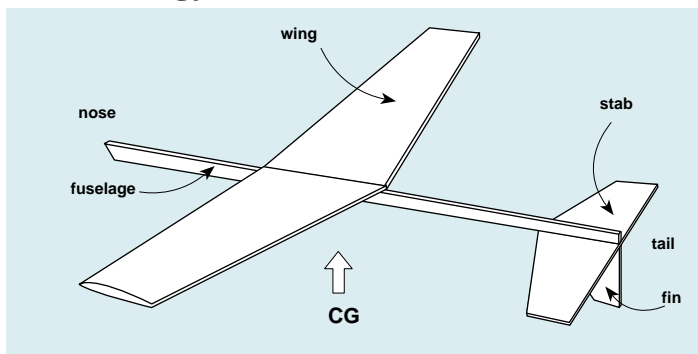
Terminology

Figure 1 - Conventional Glider Configuration

The basic parts of a glider are shown in figure 1. This configuration is typical of standard, high performance boost gliders. We will see that other arrangements of the main aerodynamic surfaces are possible, as with the Space Shuttle which combines the wing and horizontal stabilizer into one delta wing.

Any object in flight, be it a rocket or glider, will react to an offset disturbing force by rotating around the _Center of Gravity_ (CG) of the object. The CG, also called the Center of Mass, is essentially the balance point of the object. Any force that acts through the CG of a rocket or glider will cause the model to accelerate in the direction the force is acting. A force that does not act directly
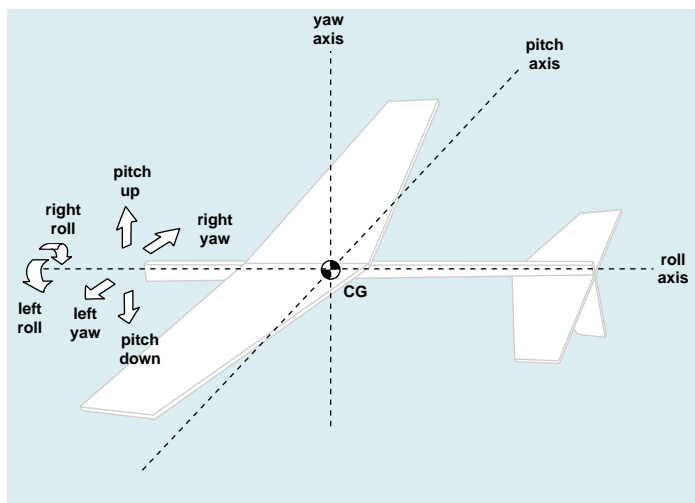
figure 2 - Rotation Axes and Motions

through the CG will also produce a torque, or turning action, that will cause the model to rotate around the CG. A torque, also called the _moment_ of the applied force, can be caused by aerodynamic forces on fins or wings, an off-axis engine thrust, or any other force acting on the model. The strength of a torque is the product of the strength of the force and the distance of the force line from the CG.

Figure 2 defines the main axes and rotational motions of a glider. A motion around the lateral axis that causes the nose of the glider to rise or fall is called a _pitch_. A motion of the glider turning to either side is called a _yaw_. A rotation around the longitudinal axis of the glider is called a _roll_.
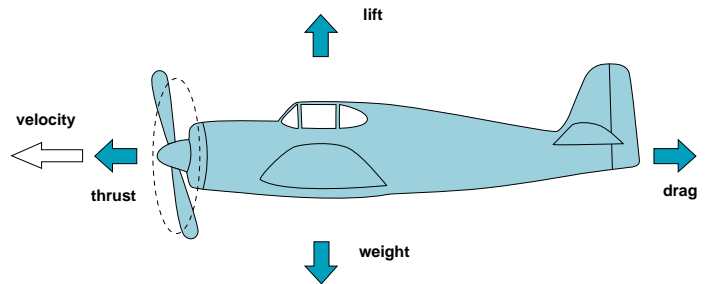
Aerodynamic Forces

Figure 3 - Aerodynamic Forces on an Aircraft

Four important forces act on an aircraft during flight, as shown in figure 3. _Thrust_ is the force provided by the airplane's engine, usually by a spinning propeller or the reaction from jet or rocket engine exhaust. A glider, after it has been launched to altitude, does not have a thrust force acting on it. _Weight_, the force of gravity acting on the mass of the aircraft, acts through the CG of the plane in a downward direction. The aircraft must counteract the weight force in order to stay in the sky. The motion of the aircraft through the air produces an aerodynamic force which we break into two components: _Lift_, which acts perpendicular (at right angles) to the aircraft's direction of motion; and _drag_, which acts directly opposite the direction of motion through the air.

For a powered airplane flying at constant velocity at a constant altitude, the upward pointing lift force is used to balance the weight force. The thrust of the engine counterbalances the drag force (which tends to slow down the airplane) so that the aircraft can continue moving forward. This forward motion is important because it creates the lift force.

A glider has no thrust force to counteract the drag force that tends to slow down the glider. As a result, a glider cannot maintain a level flight at constant speed and altitude. An aircraft in steady gliding flight is always descending relative to the air around it. The glider is essentially trading off altitude to maintain its velocity. Figure 4 shows the balance of forces acting on a glider descending in a steady glide at constant velocity.

The glider follows a path which slopes at an angle below horizontal called the _glide path angle_, which we denote by the Greek letter γ. The direction of the glider's motion along the glide path is shown by the velocity arrow on the diagram. (Notice that the glider's longitudinal axis is not pointing along the direction of motion, but
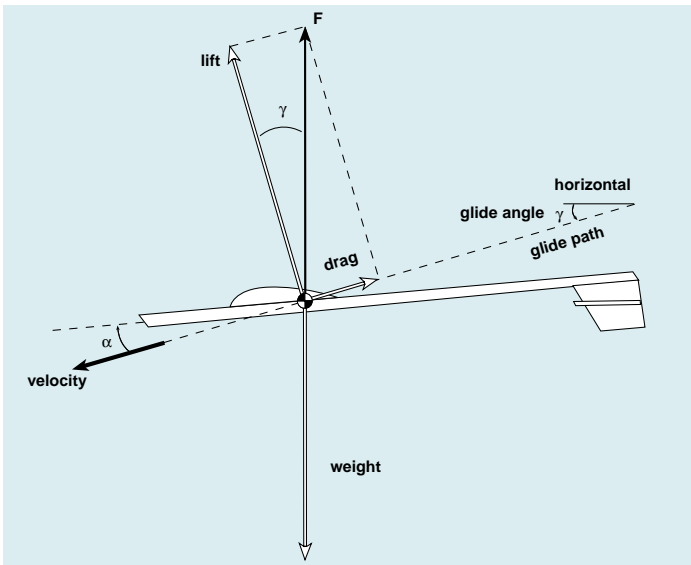
Figure 4 - Balanced Forces on a Glider

slightly above the glide path at angle α, called the *angle of attack*). The lift force, which always acts at a right angle to the velocity through the air, is tilted forward from vertical at an angle equal to γ. The lift and drag forces on the glider add together as shown to form the resultant force F, which balances the weight force. Because all forces on the glider are balanced there is no net force to cause an acceleration, so the glider will continue at constant velocity, moving along the glide slope at constant speed (this is Newton's first law of motion in operation, by the way).

The angle of the glide slope depends on the ratio of the lift to the drag (L/D). The larger the lift-to-drag ratio is, the shallower the glide slope and the farther the glider will travel horizontally before reaching the ground. Some full-sized sailplane gliders have L/D ratios as high as 40. A typical model rocket boost glider may have a lift-to-drag ratio around 3. Contrary to what you might expect, trimming your glider to fly at its maximum L/D will allow it to fly farthest horizontally, but it will not result in the greatest *duration* (the length of time in the air). Duration depends on the sink rate, or downward velocity, which depends on the glide angle *and* the glide speed. Maximum duration is achieved by trimming the glider to fly at a higher angle of attack, which results in a slower glide speed that more than compensates for the slightly steeper glide slope.

Lift and Drag

As an object moves through the air, it experiences an aerodynamic force. Lift is the component of that aerodynamic force which acts perpendicular (at a right angle) to the direction of motion through the air. Air flowing past the wing of an airplane produces the lift that keeps the plane in the air. Lift is also the force that acts on the fins of a regular model rocket to keep it stable in flight.

Drag is the component of the aerodynamic force that acts in the same direction as the relative airflow. Any time lift is produced, you also get drag — it's unavoidable. But an efficient glider wing will produce as much lift as possible with as little drag as possible. This is accomplished by using wings with specially shaped cross-sections called *airfoils*.

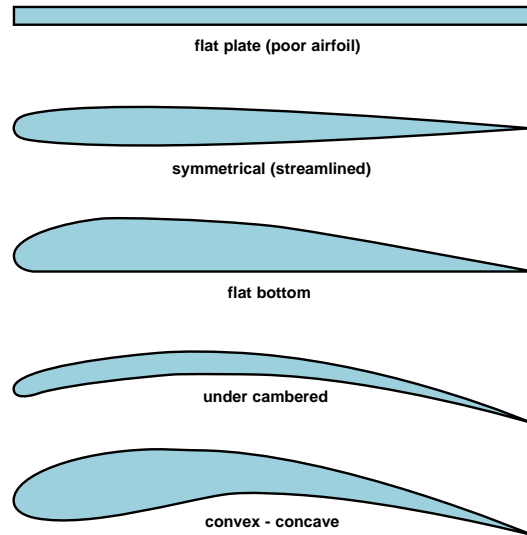Figure 5 shows a selection of different airfoil shapes.

Figure 5 - Airfoil Shapes

Figure 6 shows an airfoil shape typically used on small boost gliders. This airfoil is certainly not the most efficient shape possible (no single airfoil shape is best for all situations) but it is fairly easy for modelers to produce this shape. The distance between the leading and trailing edges is called the *chord* (or chord length) of the airfoil. The reference line drawn between the leading and trailing edges is also sometimes called the chord (or chord line). The maximum thickness of the airfoil is typically 5% to 15% of the chord length. The high point of the airfoil is located 25% to 35% of the chord length back from the leading edge. The leading edge may be rounded (as shown) or may be nearly sharp. The trailing edge has a sharp taper.
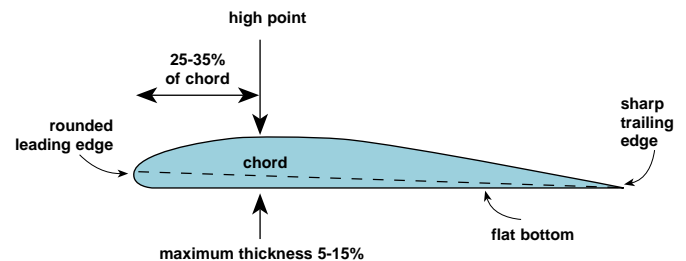

Figure 6 - Typical boost glider wing airfoil

How does an airfoil produce lift? Figure 7 shows an airfoil held at *angle of attack* (α) to the *relative wind* coming at the air foil with speed v (this is equivalent to the airfoil moving forward at speed v through still air). You may think that the air flow hitting the underside of the tilted wing produces the lift force, but that is only partly correct. The angle of attack and shape of the airfoil causes the air moving over the top of the wing to move faster than the air moving over the bottom of the wing.
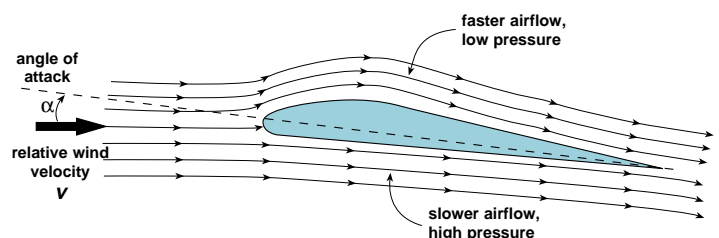

Figure 7 - Airflow past airfoil

This results in a high pressure area under the wing and a low pressure area above the wing, resulting in the lift force. In fact, most of the lift (about two-thirds) results from the suction of the low pressure area above the wing.

The amount of lift and drag produced by a wing is described by the equations:

$$L = \tfrac{1}{2} \, \rho \, C_L \, A \, v^2 \qquad \text{(Eq. 1)}$$

$$D = \tfrac{1}{2} \, \rho \, C_D \, A \, v^2 \qquad \text{(Eq. 2)}$$

where ρ is the density of air, A is the wing area, v^2 is the square of the air speed (v times v), C_L is the *lift coefficient*, and C_D is the *drag coefficient*. The lift coefficient depends on several factors including the wing's airfoil shape, aspect ratio (defined later), and the angle of attack. Figure 8 shows how the lift coefficient (C_L) changes with angle of attack for a typical boost glider airfoil*. The angle of attack is measured between the chord line of the airfoil and the relative wind direction (the velocity vector) as shown in figure 9. As the angle of attack increases, C_L increases and the wing produces more lift. Notice that the airfoil shown produces lift at a zero angle of attack, and even produces some lift at small negative angles of attack. This effect is typical of *cambered* airfoils which have an upward bulging shape. At a certain (negative) angle of attack the airfoil produces no lift; this occurs when the *zero lift line* (see figure 9) is parallel to the relative wind. The zero lift line can be approximated by drawing a line connecting the trailing edge to a point halfway between the upper and lower wing surfaces at 40% of the chord length back from the leading edge (see figure 9).
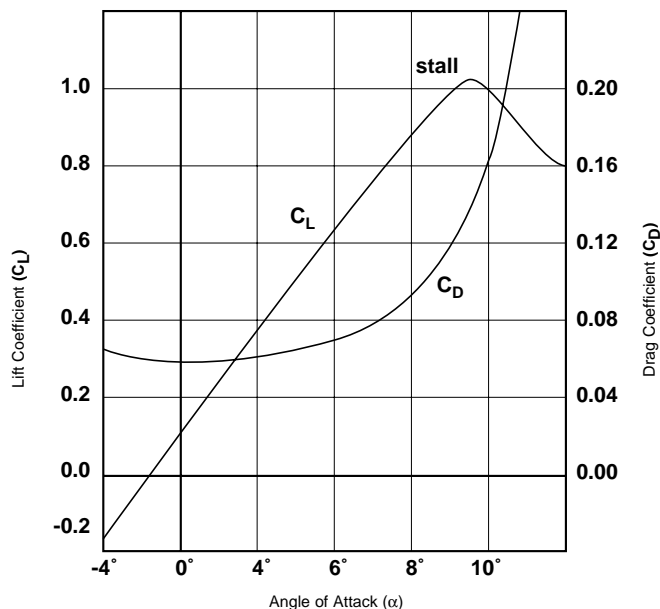

Figure 8 - Lift and Drag Coefficient vs. Angle of Attack

(*Note: The C_L and C_D plots in this report are presented only to illustrate airfoil behavior. Very little experimental data exists for thin airfoils in the Reynolds number range applicable to boost gliders. Take these plots with a grain of salt)

A symmetrically shaped airfoil (even a flat plate "airfoil") will also produce lift when held at an angle of attack to a relative airflow; but these profiles produce more drag for a given amount of lift than do properly shaped cambered airfoils. A symmetrical airfoil produces
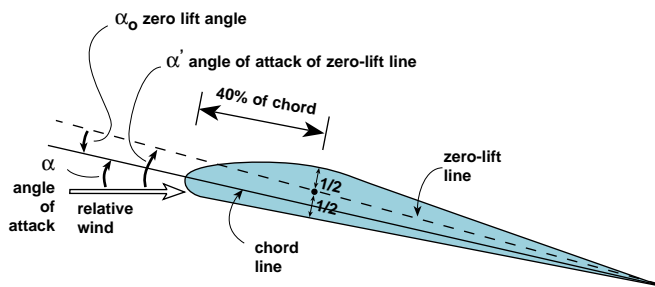

Figure 9 - Zero-lift line of an airfoil

zero lift at a zero angle of attack (its zero lift line runs along the line of symmetry).

The lift produced by a wing increases as the angle of attack increases — but only up to a point! Beyond a certain angle of attack, called the *stall angle*, the lift produced decreases (notice how the C_L plot drops off for larger α). The wing is said to *stall* (this has nothing to do with the engine of an airplane stalling; this is an aerodynamic effect). At the same time the lift of the stalled wing is decreasing, the drag on the wing continues to increase rapidly (see figure 8). This is a bad situation for an aircraft; if not immediately corrected, the drag will slow the aircraft, the lift will decrease further, and the aircraft will plummet.

What causes the wing to stall? Remember, it is the pattern of airflow past the wing's airfoil that produces lift. When the angle of attack of the wing increases beyond the stall point, the layer of air flowing over the top wing surface separates, creating a large turbulent wake behind the wing. The low pressure area above the wing which provides most of the lift is destroyed and the lift drops, as shown in figure 10. A smoothly rounded leading edge can help keep the boundary layer attached, which is one reason good airfoils have this feature. A flat plate airfoil has very poor stall characteristics.
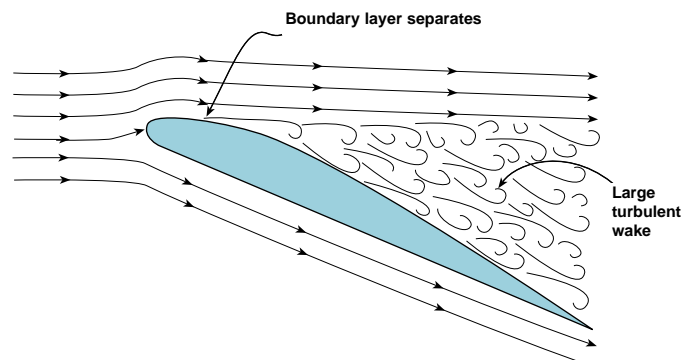

Figure 10 - Airflow past stalled wing

Sources of Drag

Where as lift is a desirable aerodynamic force, drag is usually undesirable, and aircraft builders (including model rocket hobbyists!) take great pains to reduce drag wherever possible. Let's look at some of the causes of drag and possible methods of reducing it.

Equation 2 shows that drag depends on a dimensionless drag coefficient (C_D). For most subsonic aircraft the drag coefficient is described by the equation:

$$C_D = C_{Dp} + \frac{C_L^2}{e\pi A.R.} \qquad (\text{Eq. 3})$$

where C_{Dp} is the coefficient of parasite drag, C_L is the wing lift coefficient, e is a wing efficiency factor, and A.R. is the aspect ratio of the wing. The first term (C_{Dp}) describes the *parasite drag*. The second term ($C_L^2/e\pi A.R.$) describes the *induced drag*, which is the drag that results from producing lift.

Parasite drag is the aerodynamic force experienced by any object moving through the air. This includes the pressure drag, skin friction drag, and interference drag on all parts of the glider. The causes of this drag are thoroughly discussed in Estes Technical Report TR-11 *Aerodynamic Drag of Model Rockets*. The drag reduction techniques described in TR-11 apply to boost gliders as well as other model rockets. Streamlined shapes, rounded in front and tapering in the rear, will reduce pressure drag. You will notice that most of the airfoils in figure 5 have this overall streamlined shape to reduce the parasite drag of the wing. Smoothly finished surfaces will reduce skin friction drag and shaped fillets in the joints where surfaces meet will reduce interference drag (but overdoing these can increase the weight of the glider). A glider with a "clean" aerodynamic design has less drag than a glider with all sorts of projections hanging out in the breeze.

Induced drag is an inevitable consequence of producing lift, as explained in figures 11 and 12. Recall that the airflow over the glider wing produces high pressure below the wing and low pressure above the wing in order to produce lift. As a result of this pressure difference, air under the wing tries to flow around the wing tip toward the low pressure area on top. But the wing is moving forward, too, so the result is a rotating vortex flow behind each wing.
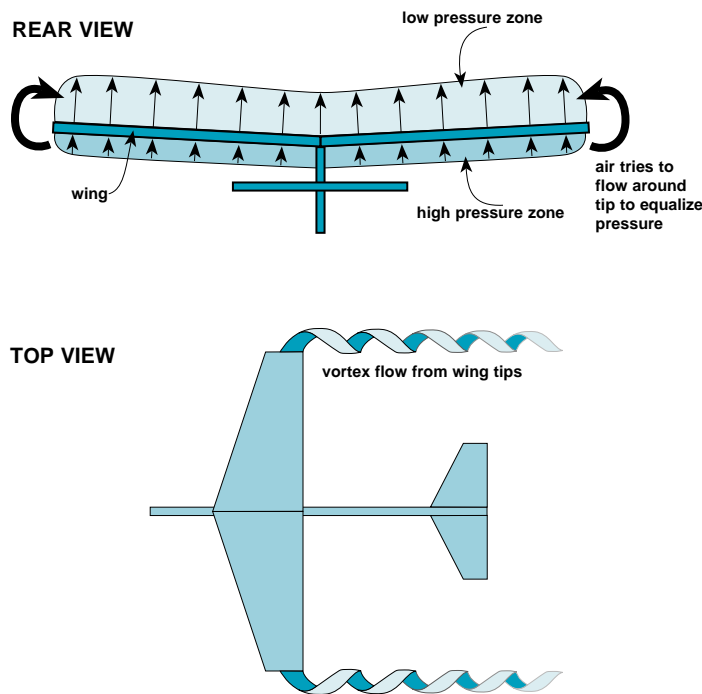
REAR VIEW

TOP VIEW

Figure 11 - Vortex flow around wing tips

The vortex flow produces a downwash of air over the

wing (strongest near the wing tips) that combines with the incoming airflow to produce a new relative airflow with a downward component (see figure 12). Because the relative wind has a downward component, the lift produced (which is always perpendicular to the relative wind) is tilted backward. The component of the lift pointing backward is the induced drag. The downwash flow also results in the wing flying at a lower effective angle of attack.

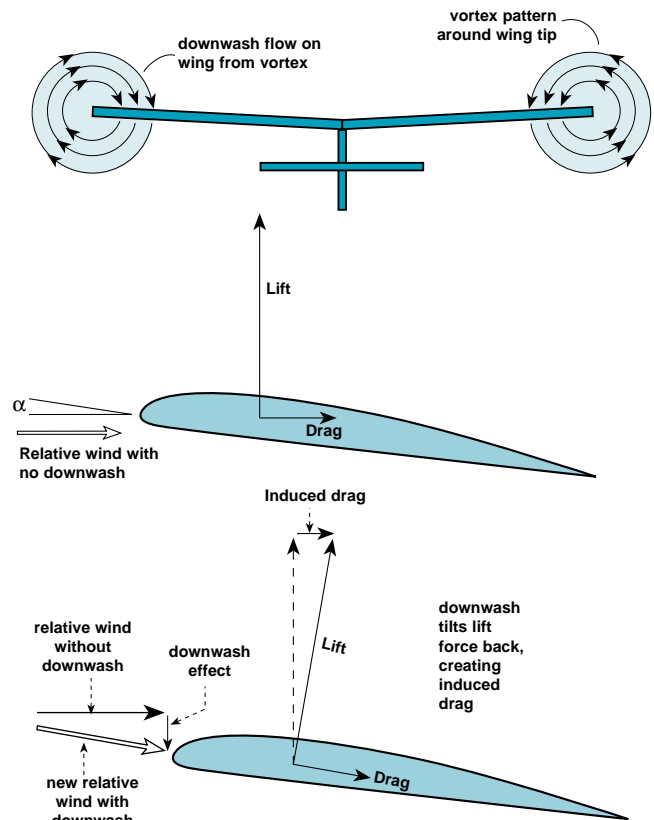The strength of the induced drag force depends on the

Figure 12 - Origin of induced drag

aspect ratio of the wing. Aspect ratio is a measure of how long & skinny or short & stubby the wing is (see figure 13). Because the induced drag is caused by flow around the wing tips, it is strongest near the tips and decreases toward the center. High aspect ratio wings have more of the wing area far from the tips, so they produce lower induced drag. Full size sailplanes use very high A.R. wings for this reason. But there is a trade-off: High aspect ratio wings are weaker and prone to structural failure at the high speeds that boost gliders experience during boost phase. As a result, boost gliders wings typically have aspect ratios below 7 (but designs such as swing wings or flop wings, discussed later, can use higher A.R. wings).

The induced drag term also includes a wing efficiency factor (e) which depends on the wing's *planform*, the shape of wing as seen from above (see figure 14). Combinations of the planforms shown are also possible (swept tapered, for example). The wing planform which creates the smallest induced drag is the elliptical planform. The efficiency factor e equals 1 for the elliptical
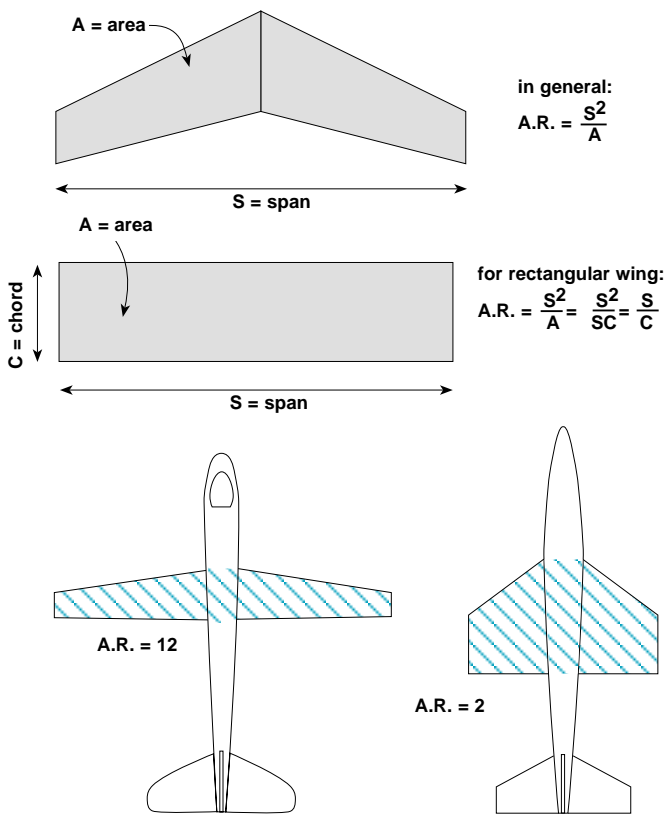
A = area

in general:

$$A.R. = \frac{S^2}{A}$$

S = span

A = area

C = chord

for rectangular wing:

$$A.R. = \frac{S^2}{A} = \frac{S^2}{SC} = \frac{S}{C}$$

S = span

A.R. = 12

A.R. = 2

Figure 13 - Aspect ratios of wings

wing, and e is less than 1 for other planforms. Although the tapered wing planform is slightly less efficient than the elliptical planform, it is much easier to make, so many boost gliders use tapered wings. The sharply swept wings used on high-performance fighter planes are not very efficient for use on model rocket boost gliders; swept wings are great at supersonic speeds, but not at slow glider speeds.
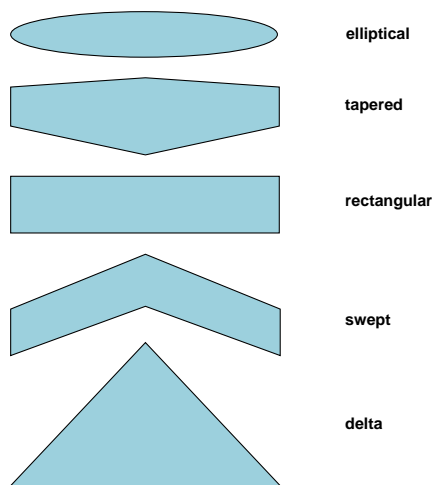

elliptical

tapered

rectangular

swept

delta

Figure 14 - Wing planforms

The shape of the outer edge of the wing tip also affects the induced drag. A rounded edge makes it easier for air to flow around from bottom to top and increases the drag. Sanding the edge of the wing tip either sharp or flat will inhibit airflow that creates the tip vortex and reduces the induced drag.

You may wonder why we can't simply glue small plates to the wing tips to inhibit the vortex airflow. In theory, this can work; in fact, some newer passenger jets have small vertical surfaces on the wing tips for this purpose. But, in practice, your tip plates would probably increase the parasite drag much more than they reduce the induced drag.

Glide Stability

A glider must fly at the proper *attitude*, or orientation in space. Stability on the pitch axis keeps the wing at the correct angle of attack to produce lift. Yaw stability is required to keep the glider pointed forward into the relative wind. Roll axis stability is required to keep the wing horizontal so the lift acts upward. A free-flight boost glider must have this stability built into the design so that it will automatically enter a stable glide after transition and recover from disturbances like wind gusts.

Pitch Trim and Stability

The wing of a boost glider is not stable in pitch all by itself. The lift of the wing is assumed to act through a point called the *aerodynamic center* which is located near the quarter chord point (1/4 of the chord length back from the leading edge). The center of gravity (CG) of the wing is typically behind the aero-center, resulting in a pitching moment that would cause the wing to pitch up and tumble end-over-end. The most common way to achieve pitch stability is by adding a second, smaller aerodynamic surface called the *horizontal stabilizer* (or *stab*). The stab produces an opposite pitching moment to counter the pitching moment of the wing (see figure 15). The glider is said to be *trimmed* (or balanced) in pitch when the upward pitching moment due to wing lift (given by x_w times L_w) is equal in strength to the downward pitching moment of the stab (given by x_s times L_s).

L_W

wing

CG

x_W

x_S

L_S

stab

stab incidence (negative)
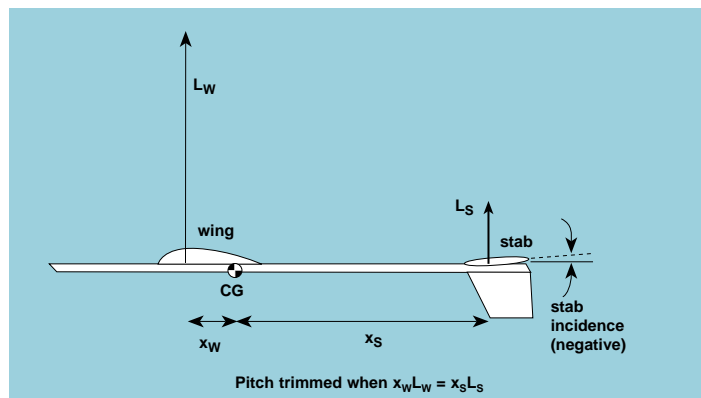
Pitch trimmed when $x_w L_w = x_s L_s$

Figure 15 - Pitch trim of a glider

When trimmed and in a steady glide, the wing of the glider will be flying at a certain angle of attack. What that angle of attack will be depends on the relative *incidence* angles of the wing and stab. The incidence angle is said to be positive if the leading edge is higher than the trailing edge, relative to some reference line.

To understand the situation better, let's start with the equation describing the trim condition

$$x_w L_w = x_s L_s \quad (Eq. 4)$$

then substitute in the definition of lift from equation 1 and

cancel terms giving

$$x_w A_w C_{Lw} = x_s A_s C_{Ls} \qquad \text{(Eq. 5)}$$

where A_w and C_{Lw} are the area and lift coefficient of the wing, A_s and C_{Ls} are the area and lift coefficient of the stab, and x_w and x_s are the distances that the wing lift and stab lift are acting from to the CG. Equation 5 shows us that there are two ways we can trim a glider. The first method involves changing the position of the center of gravity. Moving the CG changes the values of x_w and x_s (see figure 15). In practice, we change the position of the CG by adding or removing weight from the nose or tail of the glider.

The second method of trimming the glider involves adjusting the relative *incidence angle* between the wing and stab. If the wing and stab are at different incidence angles, they will meet the relative wind at different angles of attack. Remember that the lift coefficient depends on the angle of attack (see figure 8). So, we can adjust the lift coefficients (the C_L values) to balance equation 5 by changing the relative incidence (and therefore, the angles of attack) of the wing and stab. In practice, we usually change the incidence of the stab by warping or shimming the trailing edge of the stab up or down as needed. Some models have adjustable control surfaces, called *elevators*, on the trailing edge of the horizontal stabilizer to adjust the trim.

So far we have discussed the pitch trim of the glider, but how can we insure that the glider will be *stable*? To be stable in pitch, the glider must return to its trim orientation after a disturbance, such as a gust of wind, changes its attitude. If the angle of attack of the glider increases, the forces on the wing and stab must change in such a way that the glider will pitch back down to its trim attitude. If the angle of attack decreases, the changing forces must cause the glider to pitch up (see figure 16).

To insure that our gliders meet the stability conditions shown figure 16 we must have the stab flying at a lower lift coefficient than the wing ($C_{Lw} > C_{Ls}$). Because the lift coefficient is related to the absolute angle of attack, this means the zero-lift line of the stab must be at a lower angle of attack than the zero-lift line of the wing.

Why does having the zero-lift line of the stab at a lower angle than the zero-lift line of the wing produce a stable glider? To understand this, you must know that the *slope* of the C_L vs. α curve (see figure 8) is roughly the same for all airfoils (it is actually slightly lower for the stab because it operates in the airflow wake of the wing, but close enough for this explanation). This means that when the glider pitches up, the C_L of the wing and stab increase by about the same amount. But won't the moments produced by the wing and stab then increase by the same amount? No, they won't, as we can see from equation 5: When the glider is flying in trim attitude, the two sides of the equation are equal to each other. But, remember that we have built our glider so that $C_{Lw} > C_{Ls}$. This means that a greater fraction of the stab's pitching
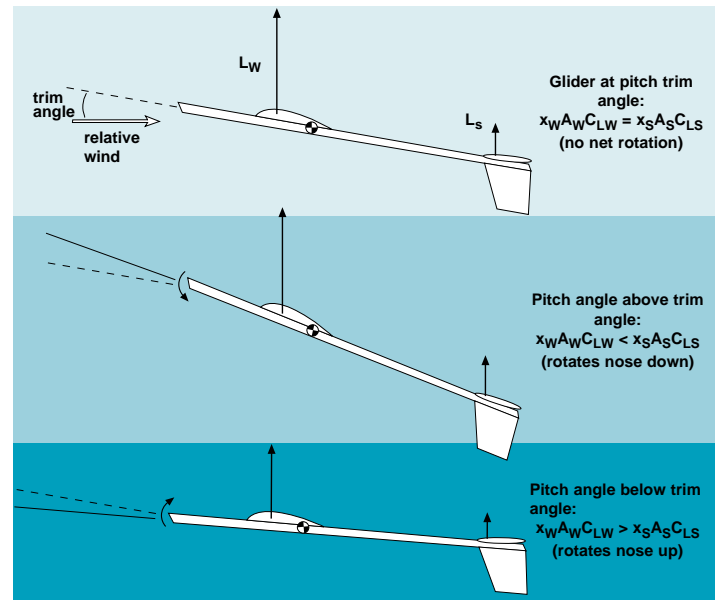

Figure 16 - Pitch moments on a stable glider

moment comes from the "x times A" part of the term, so the C_L of the stab has a greater effective lever arm than does the C_L of the wing. Therefore, when C_{Lw} and C_{Ls} increase by the same amount, the pitching moment of the stab (with its greater effective lever arm) will increase faster than the pitching moment of the wing, and the glider will pitch back down toward its trim attitude. An opposite situation occurs if a disturbance causes the glider to pitch below its glide trim angle: The lift coefficients of both wing and stab decrease by about the same amount, but this causes the stab's pitching moment to decrease faster than the wing's, so the resulting moment causes the glider to pitch back up toward its trim attitude.

For convenience of construction, most boost gliders have the wing mounted flat on the fuselage (at nearly 0° incidence). The horizontal stabilizer is then typically attached to the glider with a negative incidence of 1 to 3 degrees, depending on the design. This puts the stab at a lower angle of attack than the wing, making the glider stable in pitch. The negative incidence of the stab is sometimes provided by gluing a shim under the trailing edge of the stab, giving some "up elevator" (see figure 17).

On a typical boost glider, the surface area of the stab is 30% of the wing area. The front of the stab is located about 2.4 times the wing chord length behind the back of the wing (assuming wing and stab aspect ratios around 5). The glide CG of a typical boost glider usually lies between 30% and 100% of the chord length behind the leading edge of the wing. Although it is possible to trim a glider to fly with the stab at 0° incidence to the wing (because the zero-lift line of the airfoiled wing is still higher than the zero-lift line of the symmetrically airfoiled stab), these "zero-zero" gliders have difficulty pulling out of a dive, so are best avoided.

Some glider designs locate the horizontal stabilizing surface ahead of the wing (see figure 18) where it is called a *canard*. To be stable, the zero-lift line of the canard must have a positive incidence relative to the wing
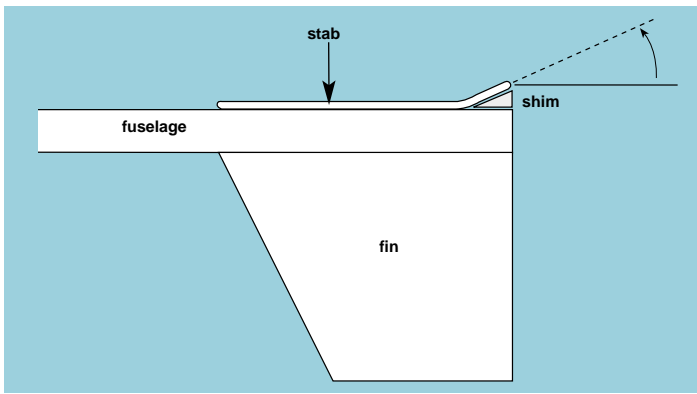
Figure 17 - Shimming trailing edge of stab for negative incidence

(canard gliders are essentially gliders with small wings in front and large stabs in back).
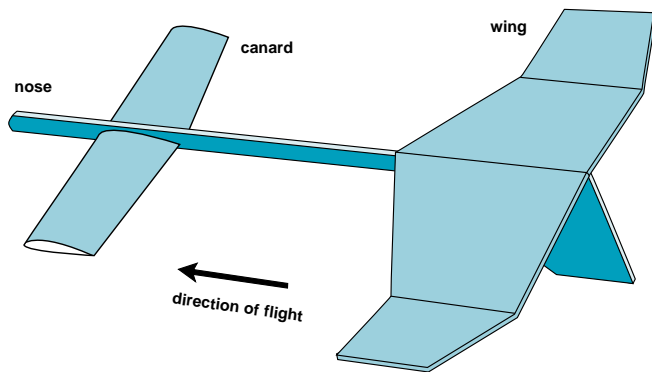
Other glider designs, like the Space Shuttle orbiter, do

Figure 18 - Canard Glider

not have a separate horizontal stabilizing surface. Instead, they use the rear section of the wing as the stabilizer (see figure 19). These gliders usually have movable control surfaces, called *elevons*, on the trailing edge of the wing that can be adjusted to provide the negative incidence necessary to keep the glider stable.
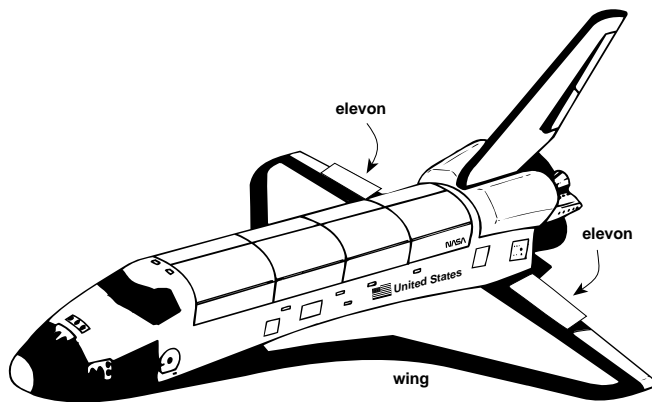

Figure 19 - Delta wing glider with elevons (no separate horizontal stabilizer)

Yaw Stability

The glider must be stable in yaw to recover from any disturbances that would turn the glider to the left or right. Keeping the glider pointed straight into the relative wind insures that the wings will produce the same lift, and it minimizes the parasite drag on the model by keeping the frontal area presented to the airflow at a minimum. Yaw stability is provided simply by adding a *vertical stabilizer* (or *fin*) at the rear of the model. The fin provides stability

in the same way the fins of a regular model rocket provide stability: If the model yaws to a non-zero angle relative to the airflow, the lift force (which points sideways in the case of the fin) creates a moment which rotates the model back into the relative wind. This works if the lateral center of pressure of the glider (as seen in the side view) is located behind the CG of the model.

The fin must be large enough to provide yaw stability, but a bottom-mounted fin that is too large can interfere with the roll stability of the model (discussed next). The fin should typically have an area that is 5% to 10% of the model's wing area. Most front-engine boost gliders have the fin attached to the underside of the fuselage to keep it out of the exhaust blast of the motor. While this may look funny compared to the arrangement on regular airplanes, it works just fine.

Roll Stability

Most free-flight gliders are stabilized in roll by using *dihedral*. The wings are attached to the fuselage at an angle (called the *dihedral angle*) with the wing tips higher than the center of the wing (see figure 20).
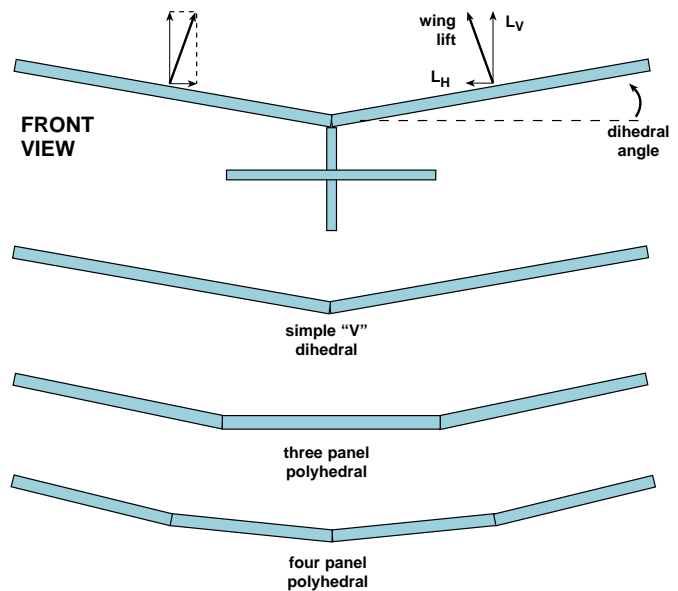

Figure 20 - Wing dihedral

The wing may use a simple "V" dihedral or may use a multiple-panel polyhedral.

The greater the dihedral angle, the greater the roll stability of the model, but too much dihedral is undesirable. Dihedral creates roll stability by sacrificing some of the wing lift; only the vertical components are available to support the glider against gravity. A dihedral angle around 15 degrees is typically used on boost gliders.

Figure 21 shows how dihedral produces roll stability. If a disturbance causes the model to roll, part of the lift force is directed to the side, which causes the model to accelerate toward that side. This sideways motion is called a *sideslip*. As seen from above, the model's actual direction of motion is now a combination of its forward and sideslip velocity. The relative wind is now approaching the glider at an angle. Figure 21c shows the glider as
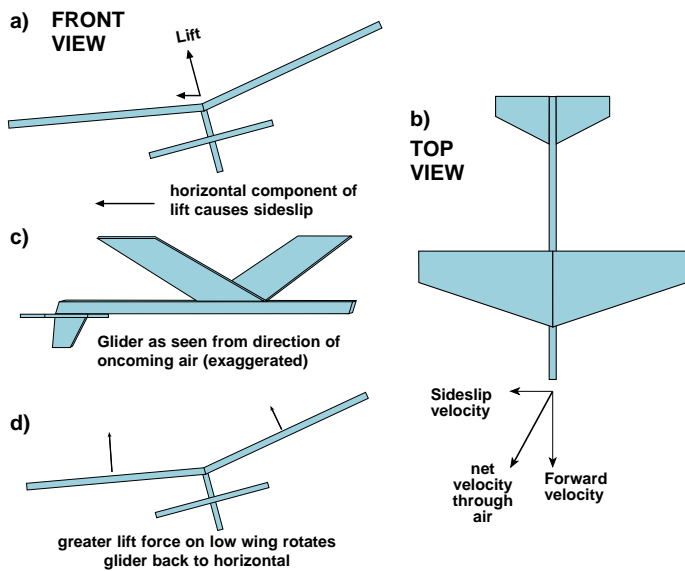
a) FRONT VIEW

Lift

horizontal component of lift causes sideslip

b) TOP VIEW

c)

Glider as seen from direction of oncoming air (exaggerated)

Sideslip velocity

net velocity through air

Forward velocity

d)

greater lift force on low wing rotates glider back to horizontal

Figure 21 - Roll stability from dihedral

seen from the direction of the relative wind. Notice that the wing on the side toward the sideslip is facing the wind at a higher angle of attack than the other wing. This wing (which was on the side of the glider that had rolled low) thus produces greater lift which causes the glider to roll back into position with the wings horizontal. Meanwhile, the yaw stability of the glider points it into the new relative wind, and the model is back in a stable glide. This last step is why the glider's fin must not be too large: A large fin may correct the yaw disturbance caused by the sideslip before the dihedral can correct the roll.

A swept wing planform also produces roll stability, as seen in figure 22. When the glider rolls and develops a sideslip, the air flows over the glider's wings at different angles. The airflow over the lower wing is closer to perpendicular to the wing's leading edge, resulting in a faster relative airspeed over the wing chord. This produces greater lift on this wing, so the model rolls back to horizontal. Ten degrees of wing sweep produces about the same roll stability as one degree of dihedral.
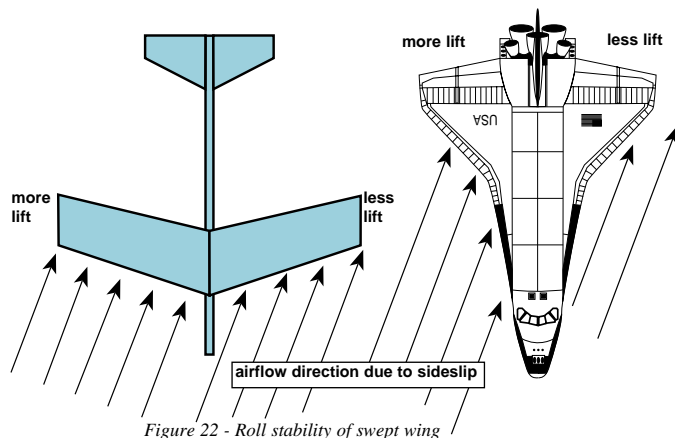

more lift

less lift

more lift

less lift

airflow direction due to sideslip

Figure 22 - Roll stability of swept wing

Turns and Spiral Dives

Boost gliders are generally trimmed to fly in a gentle turn which keeps the glider over the launch area for a longer time and makes it easier to recover. The turn is usually produced by adding a small amount of weight to one wing tip of the glider. This causes a shallow *bank*, or roll angle, which directs the lift vector slightly to one side, producing the turn. A turn can also be produced if the stab is attached at a small tilt angle (no more than 2 degrees from horizontal) so that a small part of its lift is directed to the side. You must be careful not to overdo the turn: If the turn is too tight, a spiral dive can result. Figure 23 shows how this problem can develop.

When the glider is following a curved flight path, the stab meets the air at a higher angle of attack, relative to the wing, than it does in level flight. This increases the
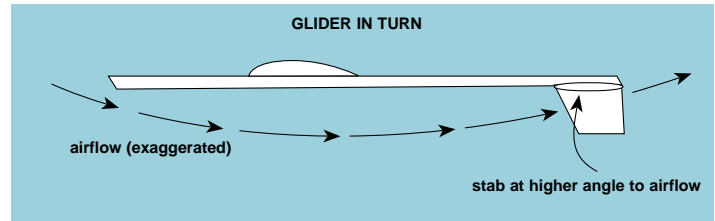

GLIDER IN TURN

airflow (exaggerated)

stab at higher angle to airflow

Figure 23 - Effect of turn on glider trim

stab's pitching moment and tends to make the glider pitch down. It also reduces the pitch stability of the glider (which depends of the relative incidence of the wing and stab). A glider requires more "up" trim in a turn than it does in level flight.

Even if the glider is properly trimmed for a gentle turn, it may run into trouble if a disturbance causes it to roll too far. If the model is too slow to correct the bank, the resulting tighter turn can cause the glider to nose down and lack sufficient pitch stability to pitch up, resulting in a spiral dive and crash. This can occur if the pitch stability margin is too small, if the dihedral angle is too low, or if an oversized fin prevents the dihedral from correcting the roll.

IV. Boost Stability

During boost, a boost glider must be a stable ballistic vehicle just like our regular rockets. The center of pressure (CP) must be located far enough behind the center of gravity (CG) to produce the correcting moments needed to keep the model pointed into the relative wind (pointed up, in this case). The profile of a boost glider is usually different when seen from the top or from the side, so the CP positions for pitch and yaw are usually in a different place; the boost glider must be stable on both axes.

Rear-engine boost gliders usually present few problems on boost: The thrust line of the engine normally passes through the CG and the rear mounted wings common on these models make them act like large-finned rockets. The pitch control surfaces (such as elevons) are normally held flat during boost, so they produce no lift forces to affect the trajectory.

Front-engine boost gliders present several boost problems, especially in pitch stability. The engine must be mounted off-center on a pylon so that the exhaust blast will not damage the model, but this offset thrust line causes a strong pitch-down moment during thrusting. Keeping the pylon low (about 1/2" for mini-engines and 3/4" for standard engines) can minimize this effect. The wing and
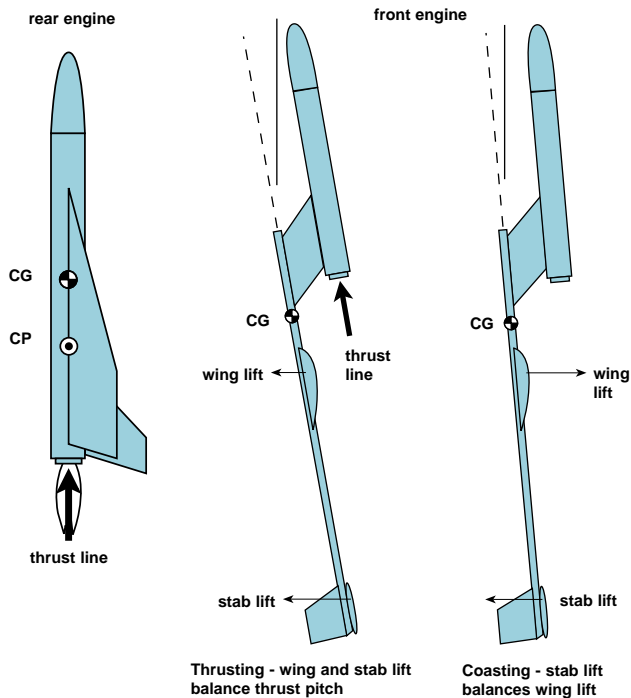
rear engine

front engine

CG

CP

thrust line

CG

wing lift

thrust line

stab lift

Thrusting - wing and stab lift balance thrust pitch

CG

wing lift

stab lift

Coasting - stab lift balances wing lift

Figure 24 - Boost stability

stab can produce large amounts of lift at the high boost velocities, so these models tend to loop or arc over in a pitch-up direction. This looping effect can be minimized by using a far-forward CG position (the front mounting of the engine helps in this regard) because this keeps the wing at a lower angle of attack.

V. Boost Glider Performance

Not all boost gliders are designed with ultimate duration performance as the primary goal, just as most of our model rockets are not designed to achieve ultimate altitude performance. Many model rocket designs are dictated by aesthetic concerns; we want our models to look impressive! But we can improve the duration performance of any boost glider, even one built primarily for its cool looks, if we keep a few principles in mind.

The glide performance equation tells us how long it takes a glider to descend through each foot of altitude:

$$t = \frac{C_L^{3/2}}{C_D} \frac{\sqrt{\frac{1}{2}\rho}}{\sqrt{\frac{W}{A_W}}} \qquad \text{(Eq. 6)}$$

where C_L and C_D are the coefficients of lift and drag, ρ is the air density, and W and A_w are the weight and the wing area of the glider. We want the value of *t* to be a large as possible to give the greatest glide duration time.

The first term, $C_L^{3/2}/C_D$, shows us that we can increase duration by increasing the lift coefficient, even if it means increasing the drag coefficient by a similar amount (because C_L in the numerator has a higher power than C_D in the denominator). This is why the maximum duration does not occur at the glide angle with the greatest lift-to-drag ratio (C_L/C_D), but occurs at a higher angle of attack. The drag increases at this higher angle (so the

glider flies slower) but value of $C_L^{3/2}$ increases even more, so the sink rate is less.

The factor W/A_w, the weight divided by wing area, is called the *wing loading*. Anyone constructing a glider can improve its duration performance by building it as light as possible. Choose lightweight balsa for construction, do not use excessive amounts of glue, and do not finish the model with a heavy layer of paint. There are limits, of course: If the model is structurally too weak, it will *shred* apart on boost.

A boost glider designer must also keep in mind that the total duration performance of the model depends on boost performance (how high the glider boosts) as well as glide performance. A feature that increases glide performance may decrease boost performance (a large wing area is an example). Another feature that improves boost performance (such as a slick finish) may decrease glide performance (due to the increased weight). Having to make trade-offs (between boost and glide performance, between low weight and sufficient structural strength, between roll stability and maximum lift, etc.) is the essence of engineering.

VI. Boost Glider Designs

Designing a boost glider that can streak skyward at over 100 miles per hour as a rocket, and then descend at less than 10 miles per hour as a stable glider, is not an easy task. Modelers have developed several methods to accomplish the transition from rocket into glider, and we will briefly describe the most common techniques. These methods fall into two general categories: Shift the center of gravity; or shift the aerodynamic surfaces. Many boost glider designs use a combination of these methods.
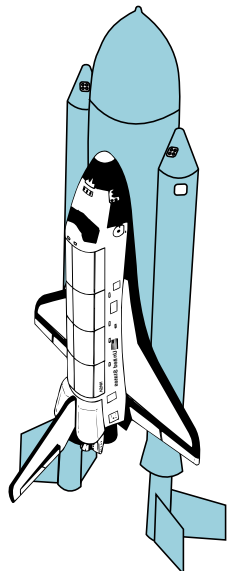
Parasite Gliders

The simplest form of boost glider is the *parasite* glider. One or more gliders are attached to a carrier rocket and released in flight. An example is the Estes Space Shuttle kit. The glider must not interfere with the stability of the carrier rocket; this can be accomplished in three ways:

1) Use a small glider on a large, very stable rocket. The forces on the glider are small and easily overcome by the fins of the large rocket.

2) Mount the parasite glider in a way that minimizes the disturbance caused by the glider. The glider can be mounted at a slight down pitch so the wing will not produce lift during boost. The glider must also be positioned in such a way that the forces which do occur will not interfere with the stable CG/CP relation of the model (the glider should be located at or behind the CG of the rocket in boost configuration).

3) Arrange multiple gliders so that any disturbing lift forces cancel each other. The Estes A.R.V. Condor kit is an excellent example.

A parasite glider is typically attached to the carrier rocket with a simple hook near the nose of the glider (see figure). When the ejection charge blows the nose cone off the carrier rocket, the reaction force causes the carrier to suddenly slow down, allowing the inertia of the parasite glider to slide it free. Supports (or two more hooks) are

Estes Space Shuttle™

Estes A.R.V. Condor™

1/8" dowel on balsa stand-off

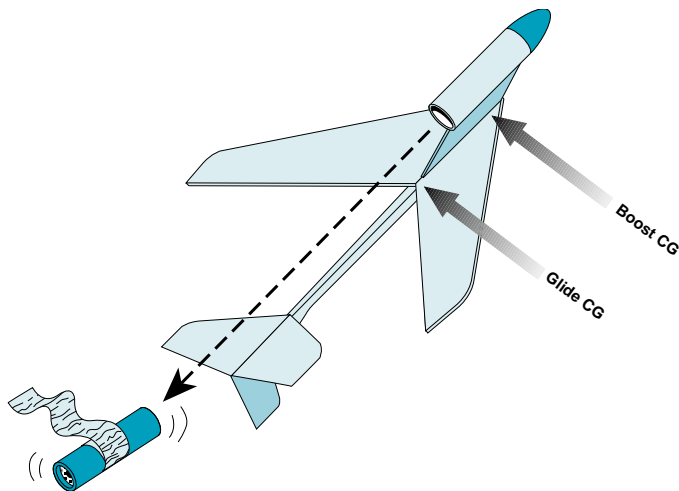launch lug

rear wing supports
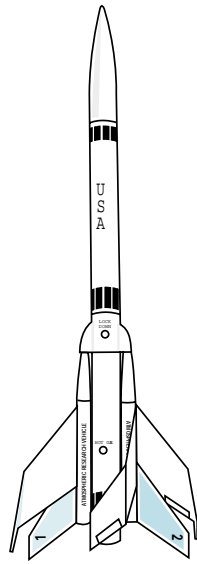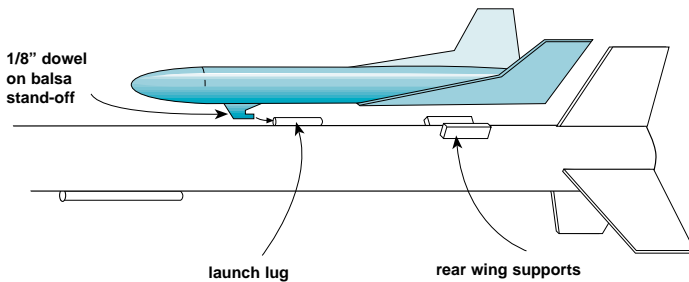
Parasite Glider Attachment

usually needed at the rear of the glider to keep it from tilting into a roll when mounted on the carrier.

Shifting the Center of Gravity

Ejecting Engine

Many front-engine boost glider designs use the CG shift that results from jettisoning the engine to make the transition from boost to glide configuration. With the engine in place at the front of the model, the CG is far forward of the center of pressure, so the model is a stable rocket. When the engine is jettisoned, the CG shifts backward to the position of stable glide trim.

Early boost gliders simply ejected the engine casing and allowed it to free fall, but this is now considered bad form. For increased safety, a streamer should be attached to the

ejected engine. This can be accomplished by using an engine mount tube that is large enough to allow a streamer to be wrapped around the engine; or, the engine could pull an attached streamer out of an additional side tube.
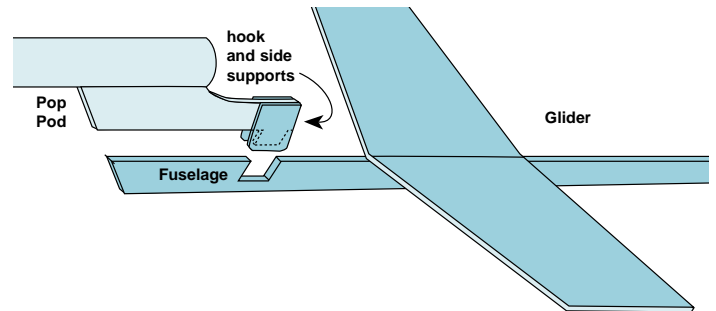
Pop Pod

The *Pop Pod* design is an improvement of the simple engine ejection method for front engine gliders. At ejection, the entire engine pod separates and deploys a recovery system. This removes as much excess weight and drag as possible from the glider to reduce the wing loading and increase glide performance. This also eliminates the safety hazard of the free-falling engine casing. The hook system that attaches the pod to the glider must be secure enough to keep wind from jiggling the glider off while the model is on the launch pad, but it must be loose enough to pop free with a gentle tap on the front of the pod. The reaction force from ejecting the nose cone and recovery system is what separates the pod at ejection.
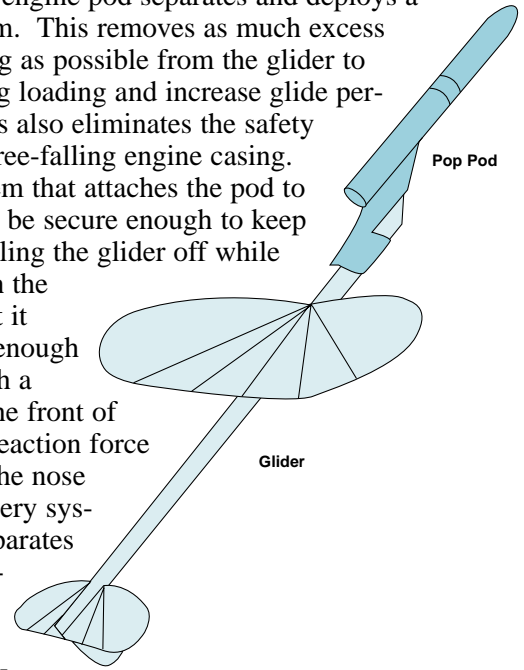
The shock cord and streamer (or parachute lines) of the pop pod should be kept short or they may snag on the glider after ejection. This results in the tangled pod and glider fluttering out of the sky, and is known as a *Red Baron*.

Pop Pod

Glider

Pop Pod Boost Glider

hook and side supports

Pop Pod

Glider

Fuselage

Typical Pop Pod Hook System

Ejecting Internal Power Pod

Rear-engine boost gliders often shift the CG from boost position backward to glide position by ejecting an internal *power pod* out the back of the glider. The pod contains the engine, additional weight up front for boost stability, and a recovery system. The recovery system is often stowed alongside the motor tube of the power pod


Boost CG

Glide CG

Ejecting Engine to shift CG

recovery system

nose weight for boost

power pod

engine
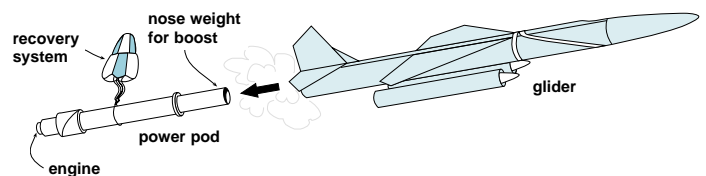
glider

Ejecting internal power pod

when the pod is inserted into the main body tube of the glider.

Ejection of the power pod often releases aero-surfaces of the glider (such as the elevator) to move into glide setting. The pod may also have fins attached at the rear which provide additional boost stability by moving the CP backwards.

Slide Pod

Recall that a *rocket glider* is a boost glider which does not eject or drop parts. One type of front-engine rocket glider that uses CG shift is the *slide pod* design. The engine pod is held in a forward position during boost, but at ejection the pod is released and elastic bands pull it backward, moving the CG to glide position.
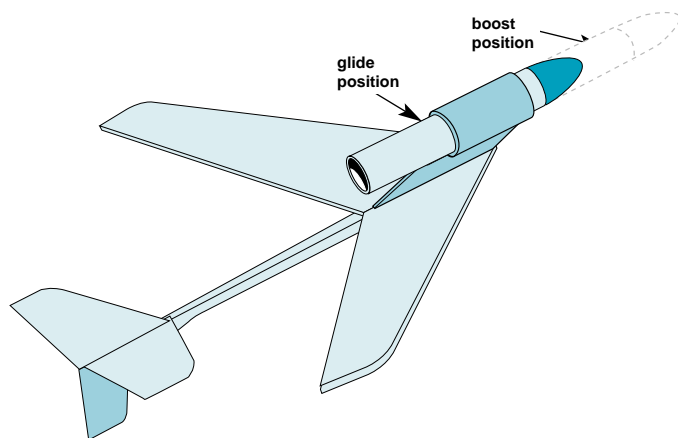

Slide pod rocket glider

Control Surface Shift

Many boost gliders employ a movable control surface, usually the elevator, that is set in one position for boost and which flips to a new position for glide. This method is commonly used on rear-engine designs: A string or hook on the power pod holds the elevator flat during boost. When the elevator is released, an elastic line or spring system moves the elevator up. The *stop* that halts the elevator in glide position may be adjustable (a nylon screw or bendable wire) to allow trimming the glider.

Radio-controlled boost gliders essentially use this same system: The pilot holds a down-elevator setting to counter the glider's tendency to loop up during the high speed boost, then transitions to glide settings as the glider slows near apogee.
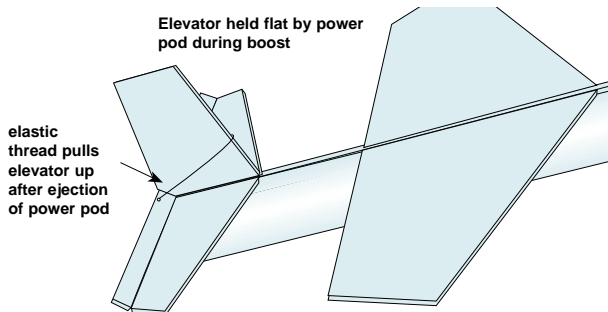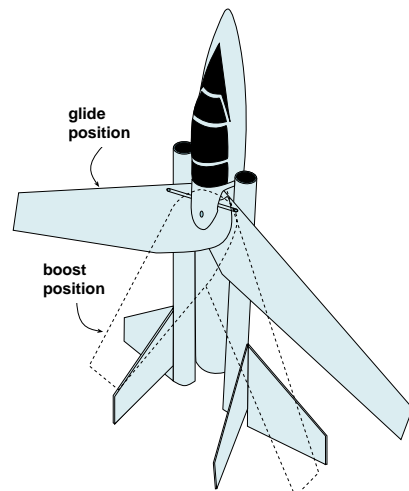

Control surface shift

Variable Geometry

Some boost gliders and most rocket gliders use *variable geometry* to transition from boost to glide by moving the aerodynamic surfaces (usually the wing). These gliders may use a latching mechanism to hold the surfaces in place until ejection, but often use *burn string* actuation (a thin string holds the surfaces in boost position until the engine's ejection charge burns through the string). Elastic bands or a spring mechanism then shift the surface to glide configuration.

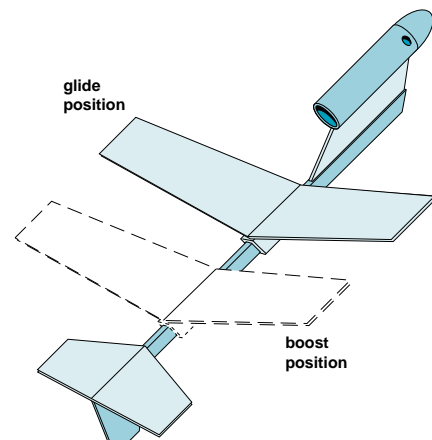*Swing-wing rocket glider*

Swing Wing

On a *swing wing* glider the wings pivot back for launch. This moves the center of pressure of the model rearward for a stable boost. It also reduces the aerodynamic forces on the wings during the high speed boost, allowing more efficient high aspect wings to be used. The Estes Tomcat is an example of a swing wing glider.

Slide Wing

The wings of a *slide wing* glider are mounted on a rail or box that can slide along the fuselage. When held back in boost position, the wings move the CP of the model well back of the CG. Elastic bands pull the wings pulled forward at ejection for glide. The glider can be trimmed by adjusting where the wings stop.

Slide-wing rocket glider

Flop Wing

The wing of a *flop wing* glider has a hinge at mid-span that allows the outer half

Flop wing rocket glider

of the wing to be folded under the root half during boost. When folded in boost position, the wing has a symmetrical airfoil shape, so it produces less lift to disturb the boost. The wing area is effectively reduced (it is now a thick wing with smaller surface area) so the CP of the model is moved back for boost. Reduced flight stresses on boost also allow higher A.R. wings (when unflopped) to be used.
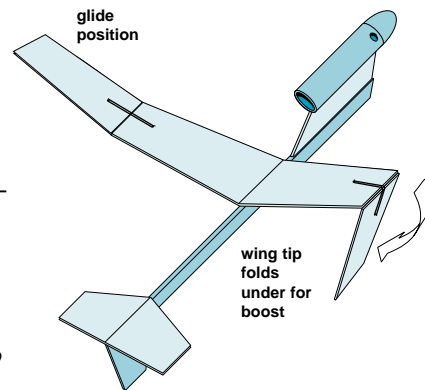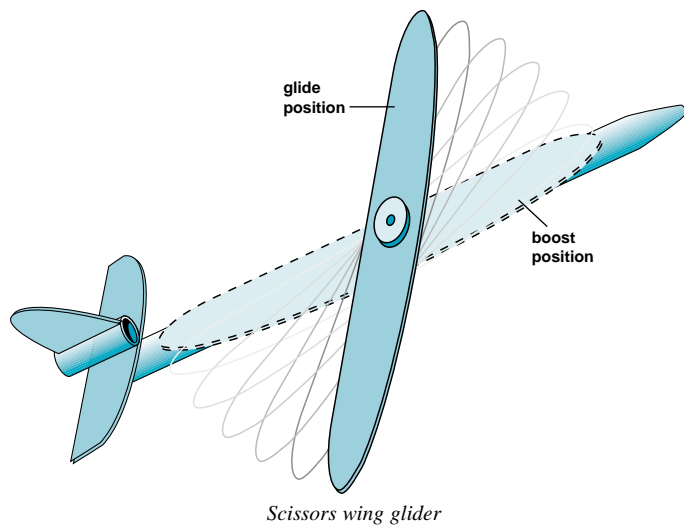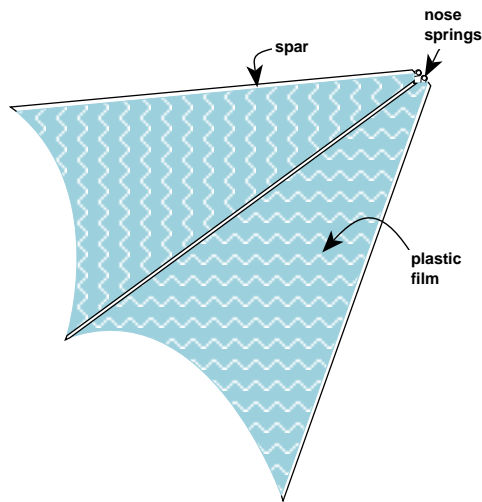
Scissors Wing

The wing of a *scissors wing* glider has a central pivot. The wing is aligned along the body tube for boost and pivots out perpendicular to the body for glide.

Scissors wing glider

Flex-Wing Gliders

Flex-wing gliders have aerodynamic surfaces made from thin plastic film attached to a rigid framework. Some gliders have used a flexible-wing on a conventional glider configuration, but most flex-wings use the Rogallo design with three spars. These flex-wings can be folded up and

Rogallo flex-wing glider (folds inside carrier rocket)

inserted inside a carrier rocket. After ejection, spring coils in the nose spread the spars and plastic film into flight position. Flex-wings have very low wing loading.

VII. Radio Controlled Boost Gliders

Remotely controlling the flight of your boost glider is a truly exciting experience, but it is not an activity that a novice can jump into and expect instant success. Before you attempt to build and fly a radio-controlled (RC) boost glider you should have some experience building and flying RC aircraft. A beginner's RC sailplane is a good place to start learning the construction methods used and the basics of RC piloting. If possible, get assistance from an experienced RC flyer before your first flight. Check with the local model airplane club; many model aviators love to help rookies learn the ropes. Some modelers also recommend learning to fly fast gas-powered model airplanes to learn how to handle the high speeds you will

encounter during boost. Unlike most boost gliders, which are ballistic rockets during boost phase, most RC boost gliders must be guided during boost, which requires quick reactions. Taking care to build your model with all surfaces properly aligned and true, and carefully following the directions, goes a long way to ensuring a safe boost.

Most beginner RC aircraft have elevator and rudder control. If you want to fly an RC boost glider with elevator and aileron control (such as the Estes Astro-Blaster and Strato Blaster) you may want experience flying an RC model with ailerons. (Note: A *rudder* is a movable control surface on the trailing edge of the fin used to turn the model in yaw; *ailerons* are control surfaces on the trailing edges of the wings used to control the roll motion of the aircraft.)

VIII. Construction and Finishing

You need to pay special attention to a few simple rules when building a boost glider:

1) Build the glider straight and true. The wing, stab, and fin must all be properly aligned and positioned and free of warps. On a regular model rocket, a fin misalignment results in a wobble during boost and some lost altitude; on a boost glider, a similar misalignment can result in a crashed model. Use your best craftsmanship.

2) Build light, especially when good duration performance is desired. Avoid excessive amounts of glue; large, heavy fillets are not required. Avoid heavy paint jobs. Sand all balsa parts smooth with 400 grit sandpaper and apply a light coat of spray paint. For optimum duration, some modelers prefer a finish of model airplane dope, or even just bare balsa colored with marker pens. Other model airplane finishing methods are useful, such as model aircraft tissue applied with dope, and iron-on film for large gliders.

Boost gliders are built primarily from balsa, but balsa varies considerably in density. Use lightweight, warp-free balsa. When sanding the wing airfoil, start with coarse grit sandpaper (100 grit) to save effort, then progress to finer 220 grit paper for final shaping. Placing the trailing edge of the wing at the edge of your work surface and using a sanding block is helpful when shaping the long rear taper of the airfoil. Finish by sanding smooth with 400 grit paper. For the thick wings of larger gliders, a razor plane can save a lot of time in the initial shaping. Very large boost gliders often use sheeted built-up wing or foam core wings. The fuselage of small gliders may be medium or hard balsa, but spruce is useful when extra strength is desired.

IX. Flying Boost Gliders
Glide Trimming

Be sure to trim your boost glider for proper glide before you launch it! To *trim*, or balance, the glider you will need to glide test it. This is best done in an open area, preferably with tall grass to cushion any hard landings, in calm conditions. If the model is a rocket glider, perform the glide tests with an expended engine casing in place.

Give the glider a gentle toss into the wind (if any),

aiming just below the horizon. Throw in a straight line, with the wings level. You should release the model at its glide speed; if you throw too hard, the model will pitch way up, stall, and land hard.

Make several test glides and watch how the model behaves (see figure). If the glider stalls or dives, you must adjust the trim, either by adding/removing trim weight, or by warping the trailing edge of the stab. Weight can be added easily by sticking small pieces of
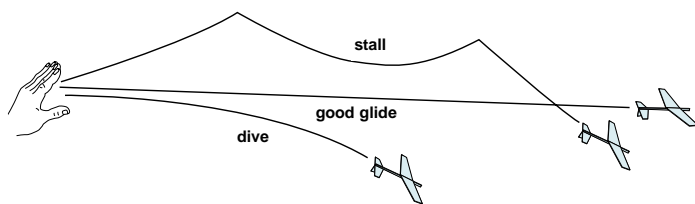

Glide testing trim of a glider

modeling clay onto the glider.

If the glider pitches up repeatedly (stalls), the CG is too far back. Add a small amount of weight to the nose of the glider (or reduce the incidence of the stab; set it for less "up-elevator"). If the glider dives, remove nose weight or add weight to the tail (or increase the incidence of the stab; set it for more "up-elevator"). If the glider turns sharply to the right or left, add weight to the wing tip on the outside of the turn.

Repeat the glide tests and adjust the trim as needed until the glider follows a smooth glide path. If the glider does not turn, add a small amount of weight to one wing tip until the model glides in a very gentle turn (not too tight!), then recheck the glide trim. Balsa surfaces can warp over time so you should check the glider's trim before each flying session.

Flying

Fly your glider with recommended engines. In general, low thrust engines are best because they avoid putting
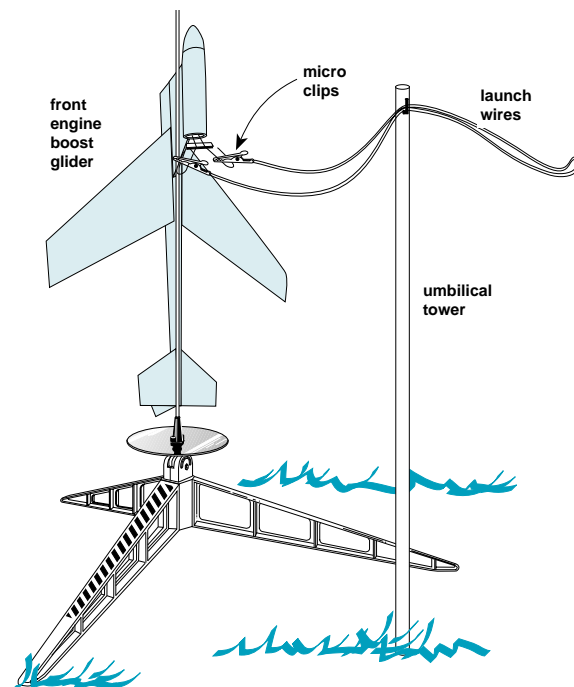
Umbilical tower prevent clips from snagging tail

too much stress on the wings. Most glider designs have high drag (compared to normal rockets) so they require short-delay engines.

When launching front-engine models, the micro-clips can snag the tail of the glider. To avoid this, set up an *umbilical tower* (a stake or other support) and tape the launch control system wire to the tower so that the clips will swing away from the model after ignition (see figure).

If the boost glider separates into multiple pieces, have someone assigned to watch and recover each part if possible. Watch the glide of the model in flight; it is easier to spot small trim errors during an actual flight than it is on a hand toss. If the model does not transition into glide (and it survives anyway), increase the incidence of the stab (more "up-elevator") and re-trim the glider using trim weight. If it turns too sharply and dives to the ground (a spiral dive) add weight to the outside wing tip to decrease the turn.

During glide, your model may encounter rising bubbles of warm air, called *thermals*, that can greatly increase the duration. Remember, a glider in a stable glide always descends relative to the air around it. But if that air is rising faster than the glider is descending, it's possible for the glider to rise relative to the ground.

X. Other Types of Model Aircraft

Modelers interested in boost gliders can learn more about how gliders work by building and flying other types of model aircraft, such as the Estes *Light Gliders*. Unlike boost gliders, which have to be built strong enough to take the stresses of a rocket launch, the Light Gliders are constructed of lighter materials, so their glide performance is superior and they are less likely to be damaged in a hard landing. They are perfect for making flight after flight to practice glide trimming and test out your understanding of glider aerodynamics.

Hand Launch Gliders

Hand launch, or *chuck gliders*, are thrown high into the air where they settle into a gentle glide. The design
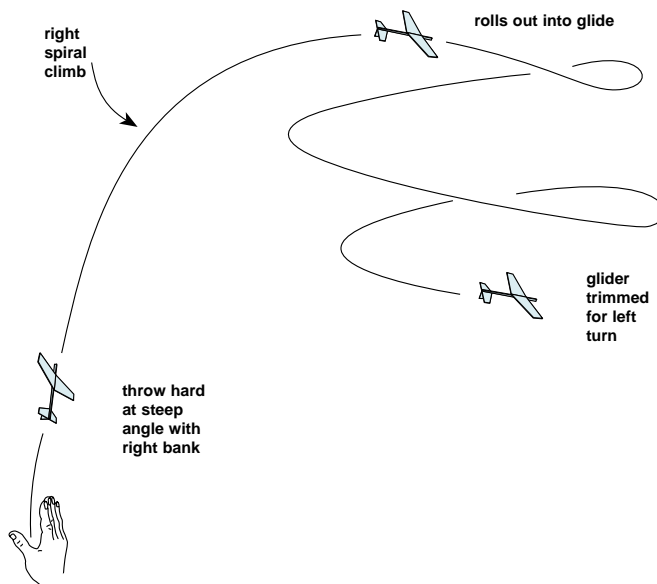

Hand launch of a glider

used in high-performance front-engine boost gliders is based on hand launch glider technology.

The stab of a chuck glider has more incidence (more "up-elevator") than a typical boost glider to enhance their glide stability (a boost glider with this much stab incidence would tend to loop violently on boost). To successfully fly a hand launch glider, trim it for a steady glide with a left turn. The model is thrown hard, with an overhand or side-arm motion, upward at a steep angle with the wings banked to the right. You are trying to achieve a right spiral climb trajectory. As the model slows down, the dihedral and left-turn tendency will level out the model and transition it into a steady glide. This takes practice, so don't be discouraged if it doesn't work right away. (If you throw left-handed, reverse the directions above.)

Tow Line Launch

A glider can be towed into the air using a string, just like you would tow a kite into the air. A loop on the end of the string slips over a backward facing hook on the underside of the glider. When the glider reaches peak altitude and the tow line is allowed to go slack, the drag on the line (a parachute or streamer is attached to the line to increase this drag) slides the loop off of the hook and the glider flies free. Radio-control sailplane gliders are launched in a similar manner with elastic tubing or a winch motor providing the pull on the line to tow these larger gliders into the air.
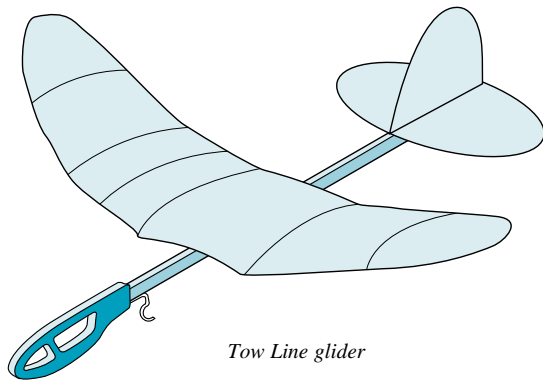
Tow Line glider

Rubber-band Powered Gliders
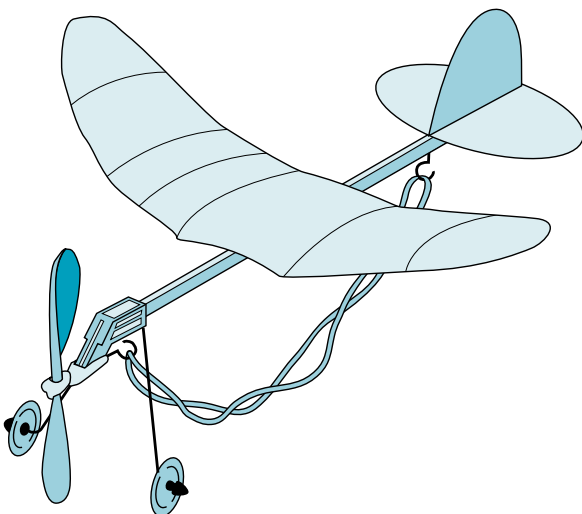
Rubber-band powered glider

A twisted rubber band supplies the energy to rotate the propeller that provides the thrust force that causes rubber powered gliders to climb to altitude. Then they return to the ground as gliders.

XI. References

TR-11 *Aerodynamic Drag of Model Rockets*, Dr. Gerald M. Gregorek. (Estes Industries)

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Basic Glider Stability, Robert Parks.

Basic Design Rules for Boost and Rocket Gliders, Dr. Gerald Gregorek.

Available at your local library: Textbooks on basic and advanced aerodynamics. The ones I happened to use are:

Theory of Flight, Richard Von Mises, Dover Publications, New York, 1959.

Foundations of Aerodynamics, Arnold Kuethe and Chuen-Yen Chow, John Wiley & Sons, New York, 1976.

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