# Aerodynamics - Advanced

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## Aerodynamic Drag

Drag on a glider is divided into two distinct types:

**1.** Air friction over the glider surface produces drag.
**Parasitic Drag ~ air density * Contact Area * $V^2$**
Where V = air speed

**2.** Kinetic energy given to deflected air in the process of producing lift for the glider takes energy from the glider and appears as a drag force.
**Induced Drag ~ $L^2/[(\text{density of air})*V^2 * b^2]$**
Where b = aircraft wingspan and
L = Lift of the wings

Note tha parasitic drag increases with square of the air speed while induced drag decreases with the square of the velocity. Also induced drag increases with the square of the lift and decreases with the square of the wing span. (more on this later)

Sailplane performance dependence on airspeed is
**Drag force = D = A $V^2 + B/V^2$**
Where A and B depend on the type of glider. Since drag causes the sailplane to lose energy and sink, the relationship for sink rate will be $V_s \sim D*V$ and

$$V_s/V_{so} = \tfrac{1}{2}\,[\,(V/V_o)^3 + (V_o/V)]$$

Where $V_s$ = sink rate
$V_{so}$ and $V_o$ are characteristic velocities.
Analysis of the shape of the curve can show that:
Minimum sink rate occurs when $V = 0.76\ V_o$.
Minimum relative sink is a minimum when $V = V_o$
V/Vs minimum is the same as maximum L/D.
So $V_o$ = speed of maximum L/D and $V_{so}$ = sink at max L/D so $V_o/V_{so} = (L/D)_{max}$
A more useful form is:

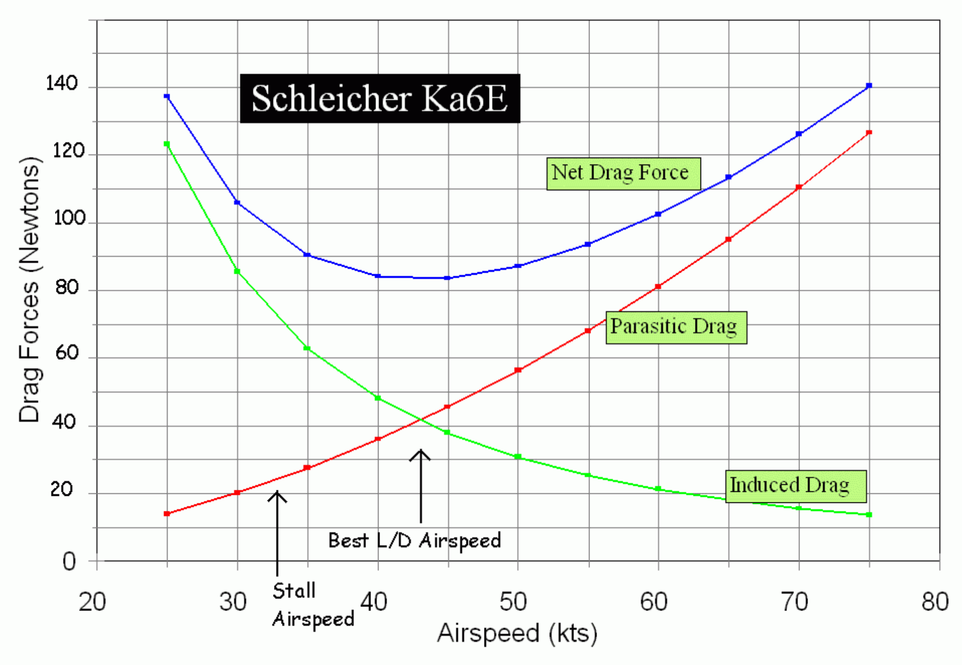
$$Vs = \tfrac{1}{2}\,V_o/(L/D)_{max}\,[(V/V_o)^3 + (V_o/V)]$$

When $V = V_o$ then $Vs = V_{so}$ where $V_o$ = speed of maximum

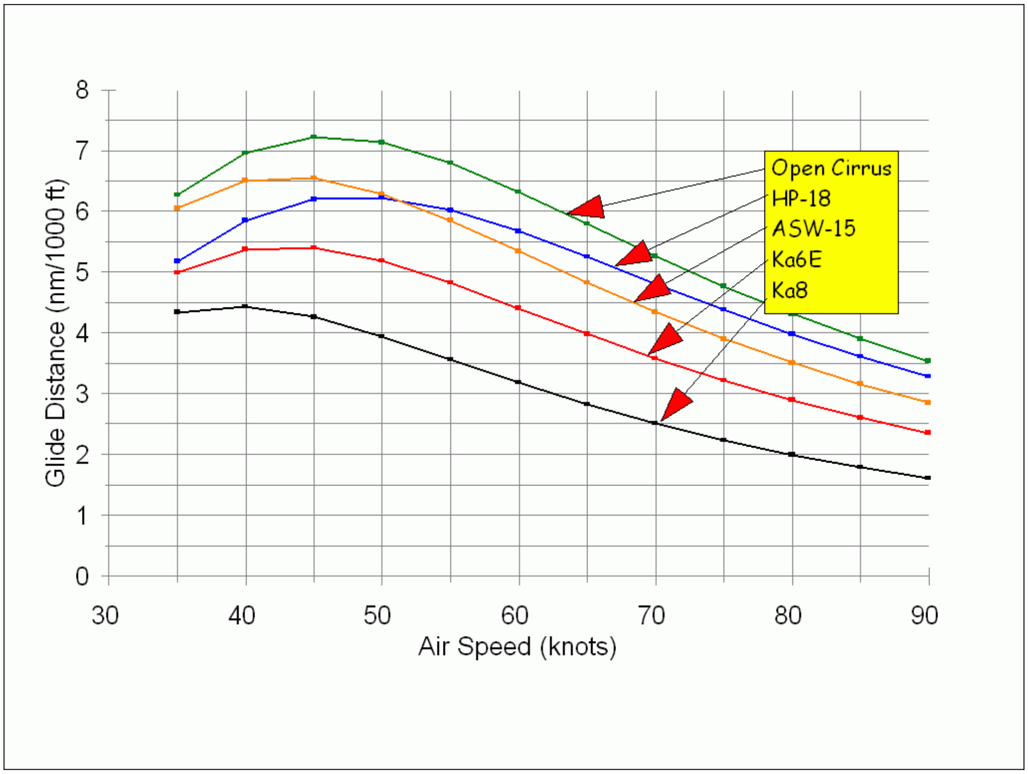
The drag force is related to the sink rate through the rate of energy loss which = D*V = $V_s$ * mg
Where mg = weight of the glider
= mass * acceleration of gravity
So

$$D = \tfrac{1}{2}\,(L/D)_{max}\,mg\,[(V/V_o)^2 + (V_o/V)^2]$$

**Example: Schleicher model Ka6e**
Empty Mass = 190 kg
Max Mass = 300 kg
**(L/D)max = 33**
**Speed of Max L/D = $V_o$ = 43 kts**
Stall airspeed at 620 lbs = 33 kts
Min sink = 36 kts
Pilot mass with parachute = 85 kg
Total mass = 190 + 85 = 275 kg (605 lbs)
Weight = 2695 Newtons



Using the $(L/D)_{max}$ and $V_o$ given here, the graph to the left showing the drag forces versus air speed was generated. Note that the induced drag equals the parasitic drag at $V_o$ (43 kts) but is larger when V is less than $V_o$. At minimum sink (33 kts) the parasitic drag is 1/3 of the induced drag.
Since the lift, in straight, level flight, is just equal to the weight of the glider, the glide ratio is just mg/D. The graph on the next page shows the L/D for several of the private



gliders in the Bluenose Soaring Club including a Ka6E.

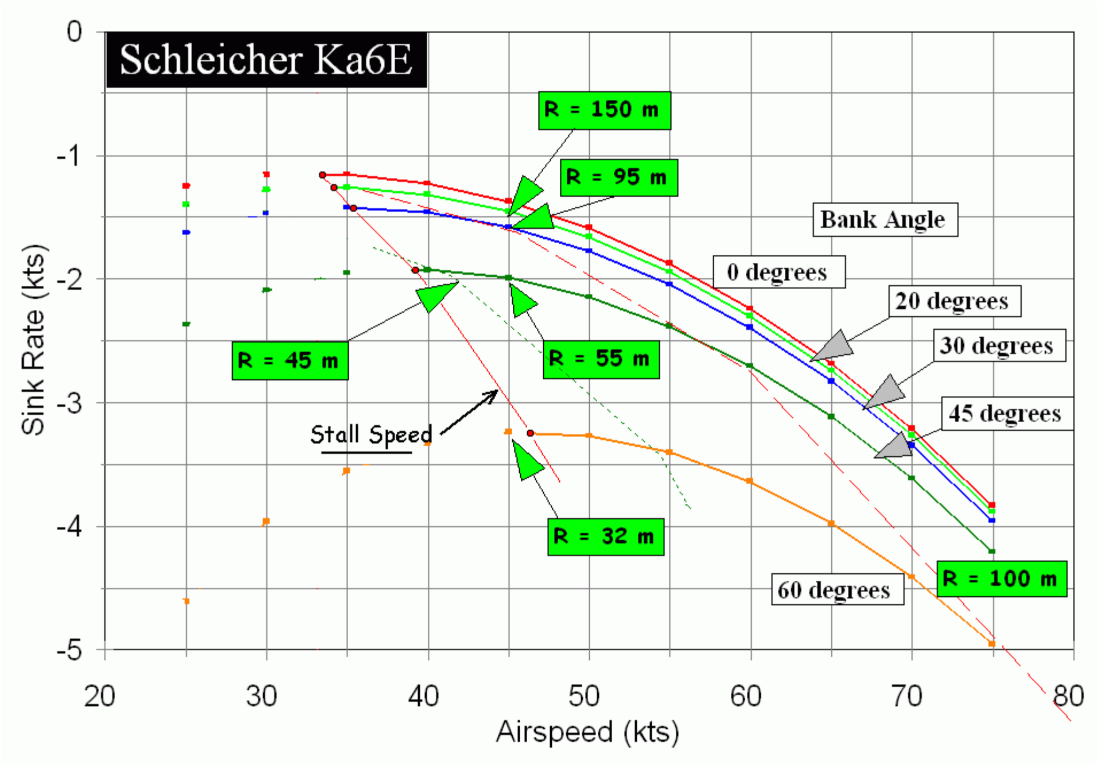
The vertical scale on the graph is in nautical mile (nm) per 1000 ft which equals 6080 ft/1000 ft = L/D = 6.08. This is a useful number to remember. If the L/D is 30 the the glide is 30/6 = 5 nm/1000 ft

## Increased Drag in a turn

The curves to the right apply only to staight and level flight. Induced drag is proportional to load squared so when a glider enters a well coordinated turn, although the parasitic drag remains unchanged, the induced drag increases.

The load factor is defined as the lift/weight. In a turn with a bank angle of $\phi$ , the load factor is 1/cosine($\phi$). The sink rate is then expressed as follows:

$$\mathbf{Vs = \tfrac{1}{2}\, Vo/(L/D)_{max}\, [(V/Vo)^3 + (Vo/V)/cos(\phi)^2]}$$

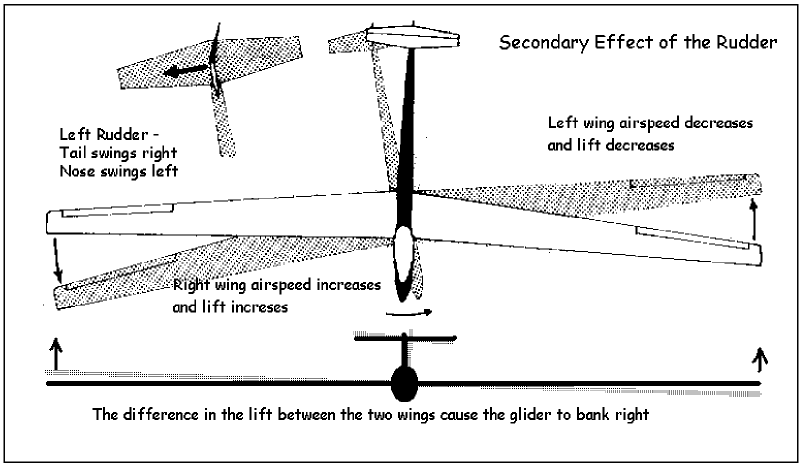


The steeper the turn, the larger the load factor which increases the sink rate of the glider. In a thermal, lift is better near the center but the glider sink rate increases as it banks steeper to turn in a smaller circle. When thermalling, a pilot has to judge what bank is best for each thermal.

The chart to the left shows the performance of the Ka6E. Sink rates are plotted for 5 different bank angles. The radius of the turns are indicated for 45 and 100 m. At 45 knots, a typical flying speed, the radius of the turning circle is given for each bank angle.

## Secondary Effect of Controls

**Rudder:**
When the rudder is applied quickly, the yaw that occurs causes one wings airspeed to increase while the opposite to decrease. This results in a larger lift on side with the higher airspeed. Thus the sailplane will bank. The diagram below shows the effect of right rudder.



**Banking Turns:**
The ailerons will bank the sailplane  and it will turn; when the ailerons are recentred it will stay in the bank. Because the glider is going in a circle with the inner wing travelling in a smaller circle than the outer wing, the outer wing will be travelling faster than the inner wing. Since the outer wing with the higher airspeed will not only have more lift but also more drag than the inner wing. Two secondary effects result.

1. The *differential drag* will yaw the glider such that I will want to turn away from the centre of the circle. To counter 'adverse yaw', rudder must be maintained to yaw the glider toward the center of the circle.

2. The *differential lift* will tend to increase the bank of the glider because the outer wing has more lift. To counter this effect,  the stick can not be held in neutral position but a slight bit of aileron must be maintained to counter the bank of the turn.

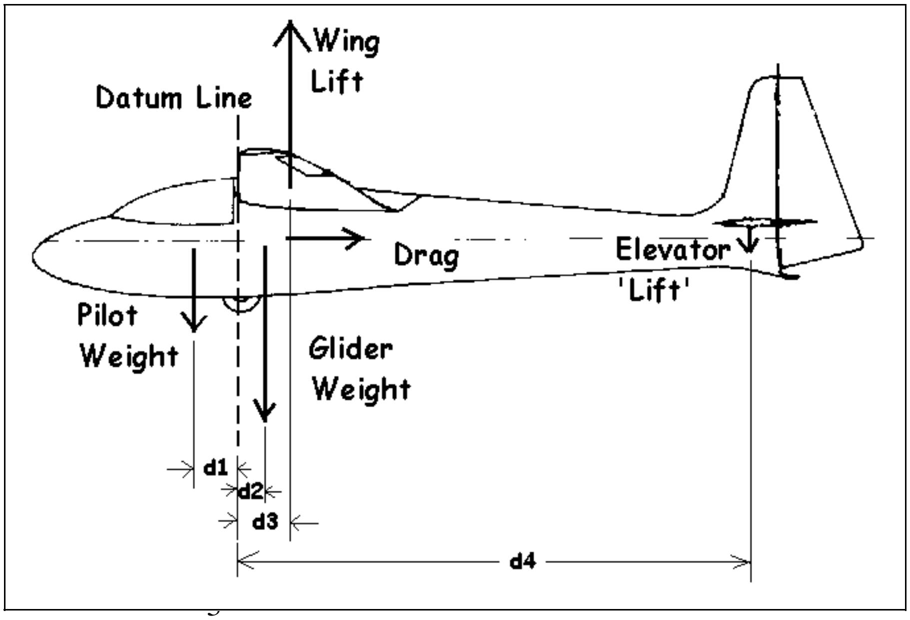
In turns that are slow or have a gentle bank, these secondary effects are small and additional rudder and aileron control is not needed.

## Torques, Weight and Balance

When discussing the forces on a glider in stable constant velocity flight, the **Lift**, **Weight**, and **Drag** are usually shown acting at the same point. There three forces must add to zero in this case. This must be true for translational acceleration to be zero.

The glider must not only not be accelerating in the up-down or forward directions, it must not be rotating. The forces that act to rotate a glider are called torques. Whereas a force will accelerate an object with mass, a torque will cause angular acceleration about a rotation axis. As is shown in the diagram below the forces on a glider do not all act at the same point. Each one will act to rotate the glider and if the sum of all their actions (torques) do not add to zero then the glider will rotate.

A torque is defined as the force acting times the distance to a parallel line through the rotation point. In the diagram, the reference line is the datum line. The torque due to the pilot's weight is $\mathbf{W_P}$ x **d1**.



Torque is positive if it tends to cause rotation clockwise and negative if it causes counter-clockwise rotation.
The sum of all the torques on the glider in this case is given below and should add to zero for constant speed flight.

$$\mathbf{W_p} \text{ x } \mathbf{d1 + L} \text{ x } \mathbf{d3 - W} \text{ x } \mathbf{d2 - L_E} \text{ x } \mathbf{d4 = 0}$$

**L** = aerodynamic lift of the glider
**W** = empty glider weight

The pilot of the glider can vary the elevator lift, $\mathbf{L_E}$, by pushing the stick forward or backward and by this mean counter the rotation caused by the other forces. Here we show the lift down but it can be up or down depending on the elevator setting. In normal flight the pilot adjusts the elevator lift with the trim so that the glider will fly with no hands on the stick. The trim is only able to apply a limited amount of force so it is necessary that the glider be 'balanced' properly for safe flight.

**Center of Gravity (C of G)**
In order for a glider to be balanced properly its center of gravity must be located within certain specified position limits. The C of G is determined on the ground with no lift present. It is that point on the glider at which it can be balanced and not rotate due to the pull of gravity.

The method of determining the C of G is to weigh the glider and add in the weight of the pilot to determine its location. The following example shows how a 'Weight and Balance' is done.

The Ka6E glider shown in the diagrams must have its C of G 18 to 38 cm behind the datum line (defined as the leading edge of the wing at rib #3) when it is at flying weight. While empty, the glider is placed on two scales; one under a support on the front and one under the tail skid. The glider is leveled during this procedure since it must be in its flying attitude. The distances from the supports to the datum line are measured (d1 and d2 in the diagram below) as well as the two weights (W1 and W2). The sum of the two weights is the weight of the empty glider, W.

$$\mathbf{W_{empty} = W1 + W2}$$

The torques produced by the two weights measured must be the same as the total weight acting at the C of G. This can be written as

$$\mathbf{d \text{ x } W_{empty} = W1 \text{ x } d1 - W2 \text{ x } d2}$$

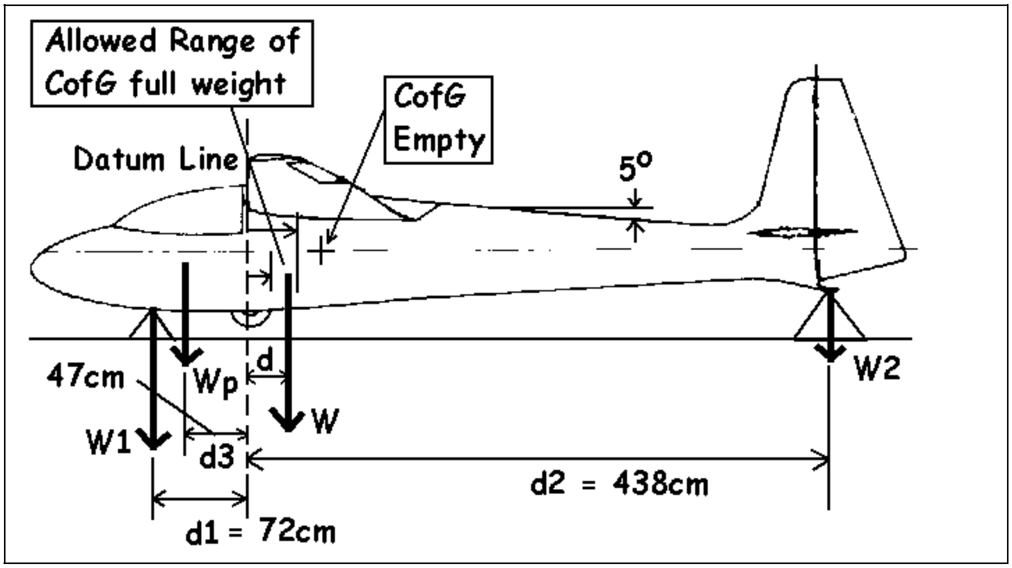
Where d = distance to the C of G (empty).
Since we have values for everything except d, we can solve for it.

Let's do this quantitatively:
Measured: W1 = 142 kg
W2 = 49 kg
d1 = 72 cm
d2 = 438 cm

$$W_{empty} = W1+W2 = 142 + 49 = 191 \text{ kg}$$

$$d = [W1 \text{ x } d1 - W2 \text{ x } d2\ ]/W_{empty}$$
$$d = [142\text{kg x } 72\text{cm} - 49\text{kg x } 428\text{cm}]/191 \text{ kg}$$
$$d = - 56 \text{ cm}$$ (negative means same as d2)

The Ka6e specifications require that the CofG ( when empty) be between 53 to 64 cm behind the datum line.
**Find the glider C of G with pilot and parachute**.
Measure:
Weight of pilot + parachute, Wp = 85 kg
Distance of pilot CofG from datum line, d3 = 47 cm.



Now sum all the torques due to the three forces, W1, W2 and Wp and equate them to the torque due to the total weight, W.

Now

W = W1 + W2 + Wp

W = 191 kg + 85 kg = 276 kg

The distance to the C of G (full weight) is given from the torque equation.

d = [W1 x d1 + Wp x d3 - W2 x d2]/W

d = [142kg x 72cm + 85kg x 47cm - 49kg x 438cm]/276kg

d = - 26 cm

This is between the required limits of 18 to 38 cm behind the datum line for the Schleicher Ka6E. If a pilot were too light then the C of G would be too far back. In this case the glider would tend to fly with a nose up attitude, stall easily and possible be difficult to get out of a spin. A pilot that is to heavy would put the CofG too far forward and the glider would be difficult to trim back to a speed for best performance. The glider would also not flare properly on landing.

## Safety Factors

All commercial gliders have been designed and tested to fly within certain stress limits. These limits are specified with maximum load factors and airspeeds. As am example, the limits for the Schleicher Ka6E are:

Maximum Allowed Load Factor (positive) = 4.0

Maximum Allowed Load Factor (negative) = -2.0

Factor of Safety = 2.0

Maximum airspeed, $V_{NE}$ =108 kts

Maximum airspeed in gusty air, $V_A$= 75 kts

Maximum Aerotow Airspeed = 75 kts

Maximum Winch tow Airspeed = 54 kts

These are different for each glider and should be memorized (along with the weight limits of the glider) by a pilot before flying that type of glider. The load factors relate to the stress that are put on the glider during flight. As we saw a banking turn is one maneuver that increases the load factor on the glider.

**Stall Speed Versus Load Factors**

The load factor, **n** , is defined as the ratio of the lift and weight of the glider **= L/W**.

As the load factor increases, the stall speed of the glider increases. This puts a limit on the minimum airspeed can maintain and still stay flying.

In straight and level flight the load factor is 1 and

$$\mathbf{L_o = W = \tfrac{1}{2} \rho C_L(max)V_{s0}^2}$$

Where, $V_{s0}$ is the stall speed (33 kts for the Ka6E). At a higher loads the stall speed, $V_{s1}$ is determined by this same relationship

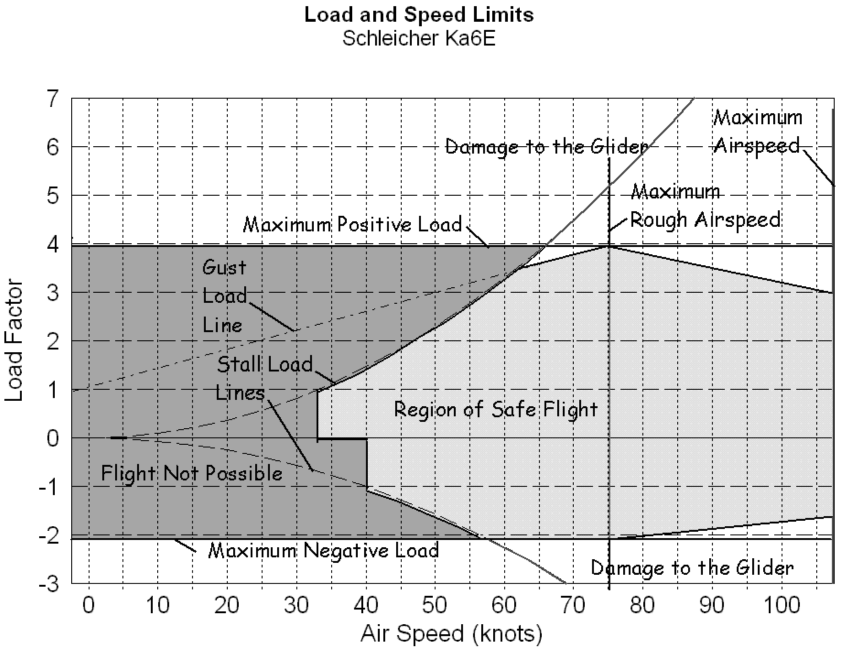
$$\mathbf{L_1 = \tfrac{1}{2} \rho C_L(max)V_{s1}^2}$$

From these two relationships the stall speed at load factor, n, can be written simply as

$$\mathbf{V_{s1} = V_{s0} (n)^{1/2}}$$

On the chart below this appears as curved line indicating the upper limit on load as a function of airspeed. To the left and above the upper curved line, flight is not possible because the glider will be in a stalled conditon. This same relationship gives the stall speed for various bank angles shown in the lower figure on page 2.

The graph to the left shows, in light gray, the region of airspeed and load factors that are safe for the Ka6E glider. The darker gray region is the region where flight is not possible because the glider will be stalled.



The unshaded region and the region to the right are areas of large load factors and airspeed which will damage the glider. The safety factor for the glider gives the factor by which limits can be increased before the the glider will break.

The glider can also have a negative load factor during brisk negative g maneuvers or in gusty conditions. A negative lift would be downward during normal flight and since the airfoil is not designed for this type of lift, its stall speed is higher. The limits on negative load factors is a downward curve defining the maximum negative load before stalling.

The safe flight region is cut off for load factors between 1 and -1 at the stall speeds. It is possible to have a glider with a load factor less than 1 but this would only be momentarily while the glider is in a semi-free fall situation and is not part of normal flight and hence the limit.

The high speed limit for a sailplane is the $V_{NE}$ or the airspeed never to exceed (108 knots for the Ka6E). This is the limit for flights in smooth air. Sometimes there is a dive airspeed limit but the $V_{NE}$ is used in this case.

### Wind Gust Loads

Wind gusts create transient increased loads on the glider, especially the wings and elevator. The gust can come from any direction. The most dramatic load increases usually comes from wind gusts up and down. Gusts from the front will also increase lift (and load) while those from the rear decrease lift and can lead to a stall when the airspeed is low enough.

It can be shown that upward gusts increase the load proportional to the gust speed times the airspeed of the glider. These gusts increase the attach angle of the wing to the flow of air. This increases the lift of the wing. The increase load due to gusts is shown as a sloped line from the load factor of 1 a zero airspeed to a limiting gust speed on the chart below. Smaller wind gusts have load lines of lesser slope.

An upward gust can also stall the glider by increasing the angle of attack enough to put the wing in its stall region. A downward gust would reduce the lift and can create a negative load in very strong gusts, hence there are limits for such gusts

The glider is limited in airspeed in rough air because of the possibility of load damage at higher speeds. The Ka6E is limited below 75 knots in rough air. This is also the limit for aerotow since tubulence from prop wash, rotor, or thermal gusts are possibly present on launch.

## Glider Design

History and Evolution (Outline)

Construction:
- Wood and Fabric
- Steel Frame and Fabric/Plastic
- Plywood and fabric (laminar airfoil)
- Fibreglas
- Carbon Fibre and Fibreglas*
  (longer thinner wings - large aspect ratio)

Type
- Primary
- Single Seat Enclosed Cockpit
- Two Seat (training method change)

Variations
- V-tails (reduce drag)
- All-flying tail
- Water Ballast
- Flying Wings
- Motor Gliders

Refinements:
- flaps (variable profile wing)
- Winglets (reduce vorices - reduce drag)

***NOTE** on drag and glider design: The total drag coefficient is given by

$$\mathbf{C_D = C_{Do} + (k\, C_L^2/\pi A)}$$

Where $\mathbf{C_{do}}$ is the coefficent for parasitic drag and $\mathbf{C_L}$ is the lift coefficient, **k** is a geometry factor and **A** is the wing aspect ratio. To reduce $\mathbf{C_D}$, decrease $\mathbf{C_L}$ and increase **A**.

**Resource:**
"*The Complete Soaring Pilot's Handbook*"
Revised Edition 1977
By Ann and Lorne Welch and Frank Irving

David McKay Co., New York, New York

*"Wings Like Eagles: The Story of Soaring in the United States"*
By Paul A. Schweizer
1988 Smithsonian Institution Press