Winged rockets and boost gliders

Introduction
One of the trickiest areas to pull off correctly in our rocketry hobby (and the nascent space tourism industry) is the flight of winged rockets. These are sometimes called 'boost gliders' because the flight consists of a rocket boost to altitude followed by a glide back down to Earth.

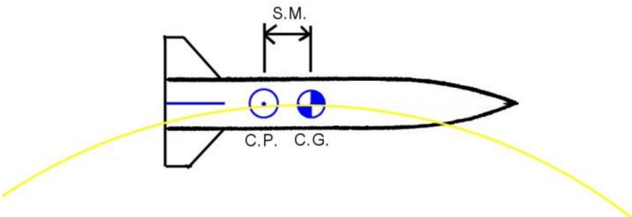
The reason they are so tricky is that the aerodynamics of the vehicle has to fundamentally change at apogee; transforming from a rocket into an aircraft, and such a major change is difficult to accomplish, as many smoking holes in the ground have proven!

Aircraft design is a thorough and complex subject, of which many good books have been written such as references 5 and 6. This paper can only give a brief introduction to the subject; I'll concentrate more on the qualitative behaviour of boost-gliders taken from my own experiences, rather than equations which will come at the end of the paper.

Words in **bold** are listed in the glossary at the end of the paper.

1: Lift
What distinguishes a rocket from an aircraft is Lift, which is defined as that component of the aerodynamic force on the vehicle that acts transversely to the direction of flight.

Let's look at a rocket at apogee:



The tailfins are counteracting the lift of the nose, so that the overall centre of lift, which in rocketry we call the Centre of Pressure (C.P.), is behind the Centre of Gravity (C.G.) and so the rocket is aerodynamically stable (see our paper 'Rocketry aerodynamics' section 4, for details of stability). The distance between C.P. and C.G. is called the Static (stability) Margin (S.M.).

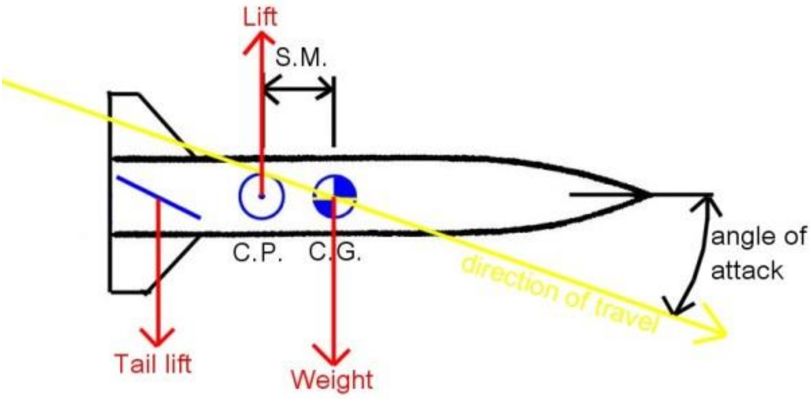
As the rocket is symmetrical, then assuming the fins are straight, the fins keep the vehicle pointing in the direction of travel as the vehicle C.G. follows its ballistic path.

Actually, the nose rapidly nods up and down a fraction of a degree or so, a simple harmonic vibration (which sensitive accelerometers can pick up).
And actually, because the trajectory at apogee has a highly curved geometry, the nose nods upwards a tad more than it nods downwards, giving a net positive average **angle of attack** which reference 2 calls the 'yaw of repose'; this causes a net lift on the vehicle which increases apogee slightly. I've seen lightweight aquajets that use this lift to create quite a glide.

After apogee, the nose will drop as the trajectory falls. How can we keep the nose up to create an angle of attack which will create lift and start a glide?
Well, the first way would be to make the C.P. and C.G. coincident. Then the nose would no longer follow the trajectory. Unfortunately, this neutrally stable vehicle (zero Static Margin) would in reality be unstable and would quickly tumble.

What we can do is create what is called ‘Longitudinal Dihedral’ which is an aircraft term that means that the forward wing (or in this case the forward lift-creating region of the fuselage) is set at a higher **angle of incidence** than the tailplane (the rearward fins).
This rule also applies if the forward wing is a canard: the forward lifting surface must be set at the higher incidence.

The simplest way of doing this is to set the tailfins at a negative angle of incidence compared to the **forebody**:



Now the vehicle is gliding: the direction of travel (of the C.G.) is shown here in yellow.
The C.P. and C.G. are not coincident (finite Static Margin for stability) but this unfortunately creates a nose-down pitching moment (called a ‘couple’) in the pitch axis: the lift and the weight are pulling in opposite directions, but are some distance apart.

The negative lift of the tailfins creates an opposite pitching moment about the C.G. to cancel-out this nose-down pitching moment and is also causing the nose to pitch up, which causes an angle of attack that creates the lift.

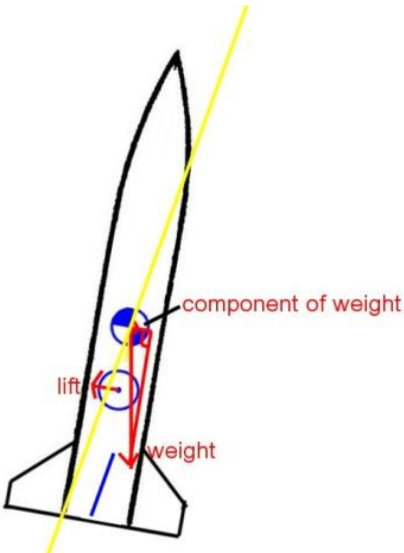
Thus a tailplane (or canard) is a device which we can alter to select a particular angle of attack on the wings or forebody.

When zero pitching moment is successfully accomplished, the vehicle is said to be ‘in trim’.

Notice that the weight vector is at right-angles to the fuselage here, i.e. parallel with the lift vector, which gives the maximum nose-down couple.

However during near-vertical ascent, the weight vector acts downwards and so its component at right-angles to the trajectory direction is very much less:

And so the nose-down couple is much less: a much smaller fin lift from a much smaller fin **angle of incidence** will suffice to keep the nose from pitching over (keep it in trim). Even a rocket with a large Static Margin can be kept vertical by small tailfin lift *provided* the trajectory remains nearly vertical: after the trajectory begins to topple over near apogee, the fins may then be too weak to hold the nose up.



Note that as the thrust line acts through the centre of gravity, the acceleration vector it causes also acts through the C.G. and so doesn't create a pitching moment. (If the thrust vector *doesn't* pass through the C.G. then you obviously *do* get a moment; this is called 'thrust vectoring').

Now fuselage (**forebody**) lift is quite inefficient; a lot of drag gets created for not a lot of lift, and large asymmetric side-forces are often created by vortices (little whirlwinds) getting shed off of the sides of the fuselage, which toss the vehicle sideways. For this reason, we add wings, which can be defined as fins that create more lift than they create drag.

Those misguided souls who build missiles tend to use very narrow wings with a huge angle of leading-edge **sweepback** (very low **Aspect Ratio**) but this is just for packaging: they have to fit within a launching rack or cluster together under the wing of an aircraft.
We are free from this constraint, so we can use much less sweepback.

The only sweep limit is then a structural one: traditional non-swept wings are prone to twisting and flutter, they can tear off. A modicum of sweepback can prevent this. Delta-wings are more rigid, so won't flutter. There's no reason to use more than 45 degrees of sweepback even if the vehicle goes supersonic.
(Airbus Defence and Space were planning to use high **Aspect Ratio**, non-sweptback wings on a Space tourism spaceplane which will re-enter at Mach 3: it's only taken them six years to realise that this idea was crazy!)

<u>The lift equation</u>
The equation for lift is **dynamic pressure** times wing **planform area** S times a lift coefficient C_L.

$$L = \frac{1}{2}\rho V^2 S C_L$$

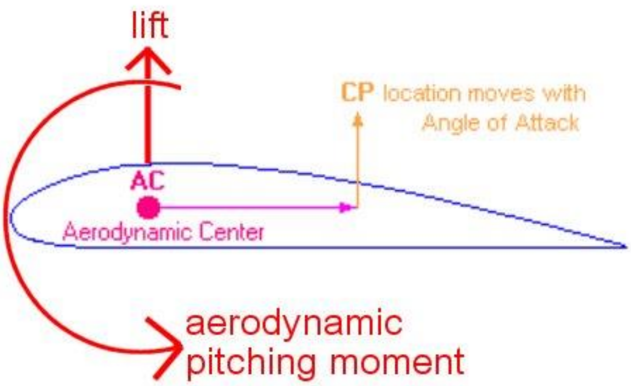
Although C_L is called a coefficient, it actually varies: it's proportional to wing angle of attack, and it also has a weak Mach number dependence; the **lift curve slope** peaks at Mach 1.

During level flight, the lift has to be made equal to the weight of the aircraft to keep it in the air. Therefore if flying at constant altitude (constant air density ρ) then as airspeed is varied, the angle of attack has to be altered to alter C_L to balance. For example, when landing, the airspeed is decreasing, so the angle of attack has to be increased by pulling back on the control column to keep the lift constant otherwise the aircraft will sink too rapidly and hit the ground hard.

2: Centre of Pressure, Aerodynamic Centre, and the Neutral Point

When we analyse a rocket's static stability, we calculate the overall centre of pressure. However, when analysing an *aeroplane's* static stability, the method is slightly different.

The wing's lift vector acting at the wing centre of pressure is mathematically replaced by a mechanically equivalent system of lift acting a little distance away from the wing centre of pressure plus a pitching moment. (This is another moment in addition to the lift-weight couple we noted earlier, and is caused by the wing's **camber** acting on the airflow).



This is done because when you analyse traditional aircraft wings, you can find a position for the lift vector, (labelled the *Aerodynamic Centre A.C.*) where this A.C. doesn't move with angle of attack up to the wing stall. This is preferred to the centre of pressure because the center of pressure moves fore and aft with changing wing angle of attack.

For the symmetrical aerofoils used in rocketry fins (known as zero **Camber** aerofoils) the fin's aerodynamic centre and centre of pressure are effectively the same (coincidental) and there's no added pitching moment, but *only* at zero angle of attack. But that's okay as most stability analyses (e.g. Barrowman) evaluate the stability only at zero angle of attack.

As wing angle of attack increases, the wing's centre of pressure position moves rearwards from its limiting position at the aerodynamic centre at zero angle of attack, back to the centroid of **planform area** as angle of attack approaches 90°.

So in a nutshell, to evaluate static stability properly for boost-gliders, we need to evaluate aerodynamic centres instead of centres of pressure. (For our rocketry fins, the aerodynamic centres just happened to also be the centres of pressure at zero angle of attack.)

Non-symmetrical (cambered) aerofoils have a higher lift; they generate lift more efficiently, but they also have a negative pitching moment (tending to pitch the nose-down) which the tailfins have to compensate for.

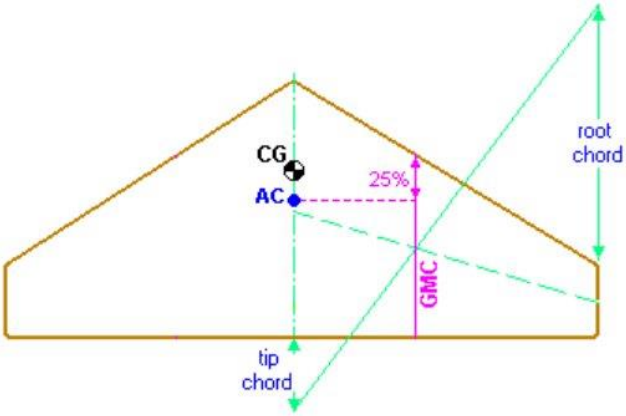
Recall how in rocketry, the overall C.P. of the whole rocket vehicle had to be behind the C.G. for stability; well for aircraft it's the same: the overall A.C. of the whole aircraft (wing plus tailplane) which is called the 'Neutral Point' (N.P.) has to be behind the C.G.
In both cases, the distance between the C.G. and the overall C.P. or overall A.C. is called the Static stability Margin.

In rocketry, the static margin is usually expressed in Calibers; its length is divided by one Caliber which is the diameter of the thickest part of the fuselage. With aircraft, the static margin length is usually expressed as a percentage of the Mean Aerodynamic Chord (MAC): the average **chord** length of the aerofoil making up the wing.

For rectangular planform wings (no sweepback) the A.C. is at the ¼ chord position, i.e. at 25% of the length of the chord measured back from the leading edge.

For Deltas it's at the ¼ chord position of the Mean Aerodynamic Chord (sometimes called the Geometric Mean Chord, GMC).

This sketch shows you how to obtain the GMC and hence the A.C. geometrically (the dashed line is the half-chord line):



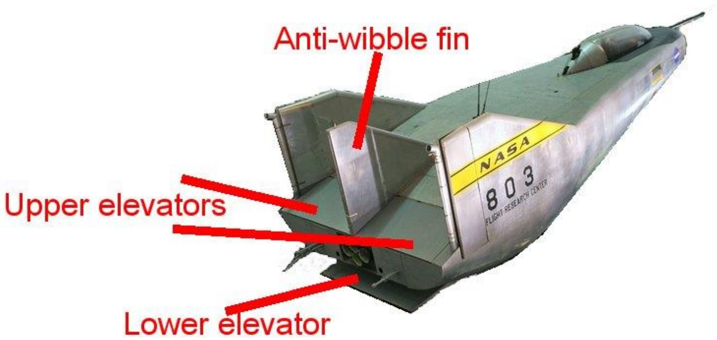
Note that Barrowman's analysis (see our paper 'Rocketry aerodynamics' and reference 1) does exactly the same thing mathematically when he calculates the fin's C.P. (A.C.)

At supersonic speeds, the A.C. moves back to the 50% MAC position.

3: Reflex

Many deltawing boost gliders have no tailplane nor canard; how can they be trimmed? What has been done is to mount large elevators at the rear of the wing that are canted upwards to create the required tail-down moment. Bending the end of the wing upwards is known as 'reflexing' the aerofoil:

The Space Shuttle used large upward-canted elevators at the rear of its double-delta wing (though it also used forebody lift somewhat as a canard).
Also, the NASA lifting bodies had upward-canted elevators at the rear of their bodies.



(This picture unfortunately shows the upper elevators undeflected as the aircraft sits in a museum.)

Are tail-less aircraft safe? Many spaceplane designs are tail-less deltas like the Space Shuttle, but occasionally tail-less aircraft can bunt violently nose-down. Burt Rutan and legendary test pilot Eric Brown both look unfavorably on tail-less aircraft.

4: Ascent and the zero-lift angle

When a boost glider is ascending vertically, it's very important that the wings generate zero lift.

Lift, by definition, is the aerodynamic force at a right angle to the trajectory, and so if the lift was not zero, the trajectory would describe a circle, i.e. a power-loop into the ground.
So it's vital that there is zero angle of attack on the wing during ascent.

Now when the wing is symmetrical (zero camber), i.e. the upper and lower surfaces have the same degree of curvature, then the angle of attack, and hence the lift, is zero when the wing (**chord**) is aligned with the airflow. This can simply be achieved, for all airspeeds, by setting the canard or tailplane at zero angle of incidence, just like a weathervane.

However, for a **cambered** aerofoil, the angle of attack which generates zero lift is slightly negative, perhaps 4 or 5 degrees negative angle of attack.

What is happening is that the graph of lift versus angle of attack doesn't pass through zero anymore, there's an offset.

The trouble is that it's very hard to estimate what this critical offset will be, and so one has to resort to 'fly it and try it' in setting the tailplane angle and that's a very unforgiving method (all those power-loops!) Better to look-up the aerofoil's data on the web to get the zero-lift angle of attack and set the tailplane incidence to achieve this negative wing angle.

5: Forebody lift

I've seen boost gliders with very long fuselages: the **forebody** is acting as a canard. The nose requires a large angle of attack to generate any lift, and it doesn't do it efficiently.

Forebody lift is very non-linear with angle of attack. A Royal Aeronautical Society formula for nose lift is:

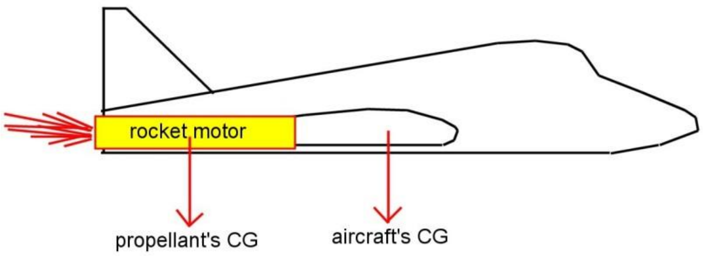
$$C_N = C_{N\alpha 0} \sin\alpha \cos\alpha + B\,(\sin\alpha)^2$$

Where $C_{N\alpha 0}$ is the **lift curve slope** at zero angle of attack, which is equal to 2.0 (per radian) at low airspeed for most nosecone shapes, and *B* is a constant for the nosecone. See our paper 'Rocketry Aerodynamics' for values of these figures.
Basically, relying on forebody lift for trim is inefficient as a lot of drag is created: more than the lift that you get.

6: The trim-toast dilemma

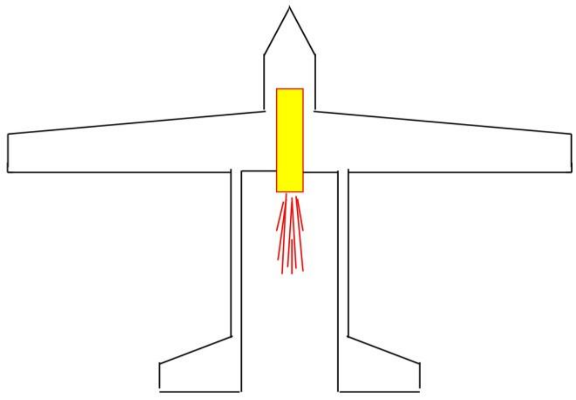
This is a phrase I coined many years ago to describe the problems you get when you mount a solid-propellant rocket motor into an aircraft. (Or have any other type of rocket engine with propellant tanks aft of the C.G.)

The problem is that any aircraft structure rearwards of the rocket nozzle would get toasted, and so you would naturally want to place the nozzle right at the back of the aircraft to make sure nothing is rearward of it.



However, as propellant is jettisoned out the nozzle, the remaining propellant mass decreases, and unfortunately, the propellant's own C.G. is significantly rearwards of the overall aircraft C.G. So the tail gets progressively lighter, making the aircraft progressively nose-heavy (the overall C.G. moves nosewards), which requires more and more elevator deflection to keep in trim and prevent a nosedive. The required elevators can get excessively large and draggy.

Twin tailbooms



Several boost-gilders have twin tailbooms separated by a wide enough gap to avoid the rocket exhaust, which allows placement of the rocket motor forwards at the overall C.G. to avoid this trim-toast issue. This is the trick Burt Rutan's Spaceship One and Spaceship Two use.

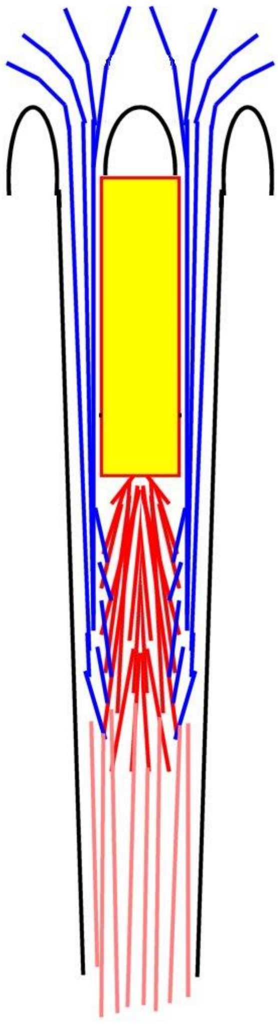
Blast tube

Another trick used by British missile manufacturers is to use a blast-tube. This is a long, insulated tube that allows the solid propellant to be mounted at the overall vehicle C.G. but the nozzle to be placed at the rear of the vehicle.

The hot blast tube runs between propellant and nozzle, the whole motor then becomes much longer. You could in theory put a two-grain propellant charge into the front of a 5-grain reloadable case along with a blast-tube of phenolic tubing, to create such a system.

With hybrid or liquid engines, it's much easier to arrange the propellant tanks to keep the propulsion system's C.G. close to the aircraft's C.G. throughout the engine burn.

The augmenter tube (or ducted rocket)



This 1920's Scottish invention is a variation on the blast tube as it allows the solid motor to be well forward, but has the added bonus that the thrust of the rocket motor can be greatly increased at low altitudes, sometimes doubled.

The system acts like a bypassed jet engine: the core engine's exhaust (the rocket motor exhaust, shown in red here) entrains (sucks and mechanically mixes) a stream of air (shown in blue here) from the bypass duct into the rocket exhaust.

This does two things: firstly the mixed rocket exhaust and air becomes a slower-moving large mass flowrate flow, which creates thrust more efficiently. Secondly, the bypass airflow flows down the side of the rocket motor and so encounters a narrower cross-sectional area to flow past. This restriction causes the bypass flow velocity to increase, and so from **Bernoulii's principle** its air pressure decreases. This lets the rocket exhaust flow into a low-pressure region, which enhances its thrust.

My theoretical analyses show that a simple circular tube (no taper) is very close to the ideal slightly tapering conical tube, and so a simple metal pipe will do, as has been borne out by my experiments on augmenter tubes. Furthermore, the greatest thrust augmentation occurs for low combustion chamber pressure motors operating at low altitudes (like our commercial HPR solids) and for low subsonic airspeeds.

Adding little strakes or vortex-creators to enhance mixing of the two flows is known as 'hypermixing' and increases the efficiency of the device: mixing will reach completion inside a shorter tube.

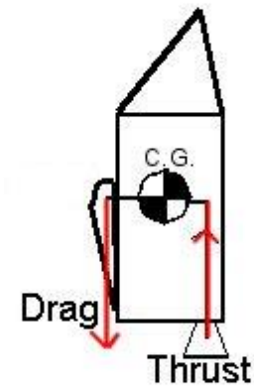
Needless to say, the rear of the augmenter tube gets seriously hot, this heat has to be dealt with.

Augmenter tubes also work at supersonic airspeeds, but their shape is then quite different which involves complicated variable-area mechanisms.

7: The thrust line

With our standard rocket shapes, we know to keep the line of action of the thrust (the thrust vector) pointing straight up the fuselage (body tube) as this means it passes right through the C.G. and so there's no thrust moment about the C.G.

What you may not have appreciated is that the thrust line is also passing through the drag centroid. If it misses this centre of drag then an aerodynamic moment is created, which is one to watch out for during vertical ascent of boost-gliders. In this sketch, not only does the thrust line miss the C.G. but the drag is acting mainly through the wing so again the thrust line misses it.



Because the thrust is such a large force, even a small moment arm (a near-miss) can cause a looping flight.

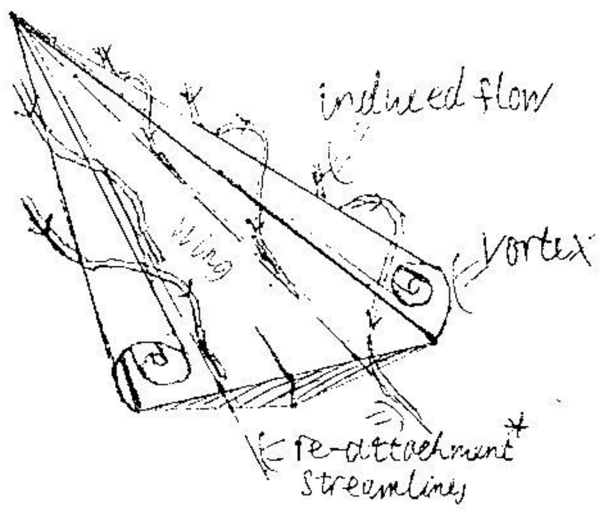
8: Delta-wing aerodynamics

Many boost-gliders use delta wings.

One of the benefits of highly-swept delta wings is their ability to remain flying at very high angles of attack, which more than compensates for their shallow **lift curve slope**.

A high angle of attack is required during take-off and landing at slow airspeeds.

Deltas keep lifting at high angles of attack that would stall a straight wing. This is due to the phenomenon of vortex lift: above a few degrees of angle of attack, the flow over the leading edge of the delta wing separates from the wing and curls into a vortex:



This spinning tame whirlwind induces flow above the vortex, which would otherwise be stalled at such a high angle of attack, to flow back down onto the wing.
Also, the rapidly spinning vortex creates lift by speeding up this induced upper flow as it passes over the vortex, reducing its pressure.

Crowding

Note that the induced upper flow re-attaches to the wing along a line known as the re-attachment streamline: as the angle of attack is increased as the aircraft's speed drops, the cone angle of the vortices increases (they get fatter) forcing the re-attachment streamlines together. At some critical angle, they merge, and the flow no longer re-attaches: this is the vortex lift equivalent of a stall, and is known as vortex crowding.

Vortex crowding affects pitch stability, since the detachment of the air down the centre of the wing alters the position of the aerodynamic centre: the upshot of this is that some deltas can have two stable aerodynamic centres, depending upon whether angle of attack is greater or less than the crowding onset angle.

Wibble

However, a delta wing aircraft will usually wibble before this happens:
'Wibble' is a term I coined back in the 90's when Viz comic was popular; one of its characters used it as a catchphrase. I use the term to describe the short period vortex-induced wobble from side-to side in the roll axis of delta winged aircraft.

What is happening is that at high angle of attack (too low an airspeed) the vortices coming off the wing leading edges are coming into contact (onset of crowding). They bounce off each other and battle for supremacy which causes a roll oscillation to develop. As one wing rolls downward, its angle of attack increases, which increases the size and strength of its wing vortex. This causes more lift on that wing which then rolls upward.

Low-aspect ratio deltas that have no large fuselage between the wings are especially prone to wibble, which can get so bad that the aircraft rolls right over and falls out of the sky.

The way to cure wibble is to build a physical wall between the wing vortices so that they can't hit each other. If there isn't a tall fuselage to act as a wall (as with the Space Shuttle) then you have to add a central wall. This can take the form of a low-aspect ratio fin set at the rear of the fuselage.

NASA's lifting bodies were especially prone to wibble: the near-fatal crash shown in the title sequence of the Six Million Dollar Man was blamed on the pilot but was actually classic wibble. NASA found from trial-and-error to add a central fin (see the picture on page 5).

Burst

Another serious problem that can occur with deltas at very low airspeed/high angle of attack is that the vortices literally run out of steam. This can occur before the onset of crowding for higher **aspect ratio** deltas.

As the angle of attack increases, the rotational speed of the vortices decreases. Eventually, at too high an angle of attack, the vortex just can't spin anymore and there isn't a vortex any more, it's just dead flow.

This is known as vortex bursting, because it happens suddenly and it looks as if the vortex has exploded, it's just not there anymore. And this is bad because you suddenly lose most of the lift and that really is equivalent to a stall.

Typically, due to tiny geometric differences at the front of the wings, one vortex will burst on one wing before it bursts in the other wing, because there's no such thing as a perfectly symmetrical aircraft, and also there is no such thing as a pilot who can fly completely straight and level with absolutely zero yaw, so again, the aircraft flips on its back and falls out of the sky.

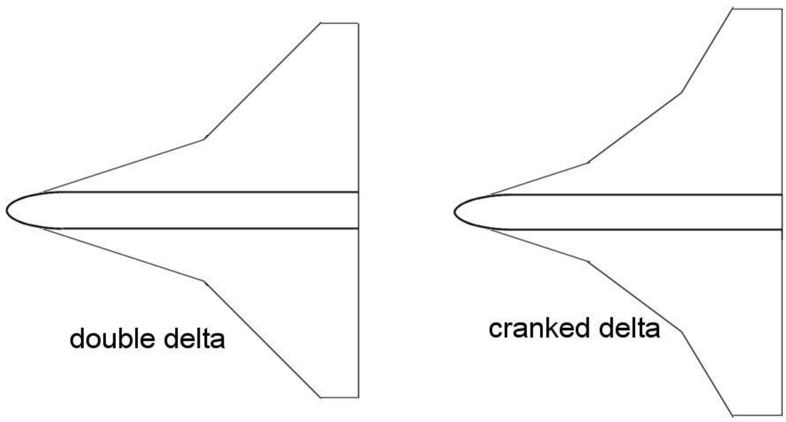
The double-delta wing

To supress vortex burst down to much lower airspeeds, the U.K. developed the double-delta wing, which was used on Concorde, then subsequently the Space Shuttle and several fighter aircraft.

At large angles of leading-edge sweepback, for example 70°, the vortices are extremely powerful, both mathematically and physically in terms of the velocity of spin and of the low pressures that they can induce.

As you reduce the sweepback angle, the power of these vortices decreases.

So what is done is that on the front of the vehicle, you have around 70° of sweepback, to spin up a very powerful pair of vortices. Then further aft, the sweepback is reduced to around 45°.

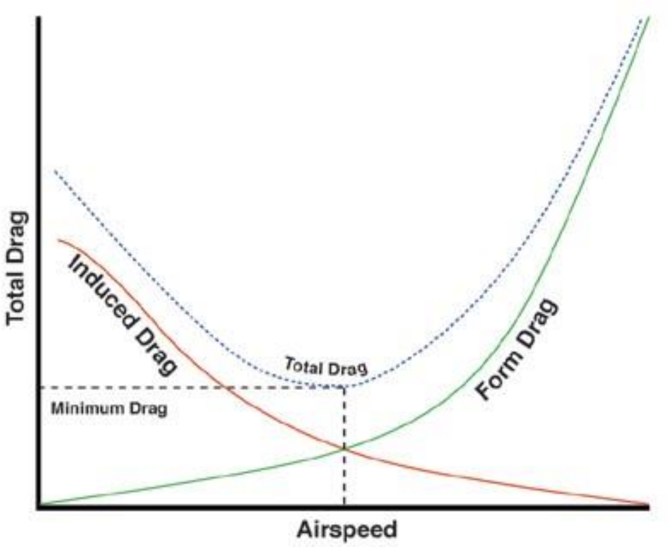


The powerful vortices forward energise the less powerful vortices rearward to literally keep them spun-up at high angles of attack.
Therefore, double-delta wings and their modern equivalent: cranked delta wings, can fly at much higher angles of attack which reduces their landing airspeed.

The back-side of the drag curve
With all aircraft, there is a particular airspeed that causes minimum drag force.

At lower airspeed, the drag created by wing lift (lift-induced drag) increases because the angle of attack has to be increased to keep the aircraft in the air, and at higher airspeed, the drag created by the wings and fuselage thickness and also skin friction, (form drag) increases.

The minimum drag airspeed is also known as the 'best glide airspeed' because the minimum drag will allow the aircraft to glide the furthest distance.



With traditional aircraft (no leading-edge sweepback) the minimum drag airspeed is just above the level-flight stall airspeed, so pilots rarely find themselves flying below this airspeed. This is just as well, because flying below the minimum drag airspeed, which is called 'flying on the back-side of the drag curve' can be very confusing.

When flying above the minimum drag speed, a glider pilot can control his glide angle by varying airspeed: more forward stick for more airspeed equals a steeper glide whereas pulling back on the stick equals a shallower glide, it feels natural.

But with deltas, the minimum drag airspeed is quite high, so during takeoff and landing you'll be flying on the back-side of the drag curve. This not only makes gliding counter-intuitive (lower airspeed rapidly makes the glide much steeper) but if you lose one of a pair of engines on takeoff, you might not have enough thrust from the remaining engine to counteract the induced drag and keep flying.

This happened to the Concorde that crashed in France: as if things weren't bad enough what with a dead engine on fire, the French maintenance crew had bolted its undercarriage on squint so the pilot had to lift off early to avoid slewing off the side of the runway. The Concorde just couldn't maintain a climb with this much induced drag. The aircraft lost airspeed, one wing's vortex burst, and the aircraft rolled on its back and fell out of the sky.

The Space Shuttle pilots devised an approach to land that avoided the backside of the drag curve until the very last moment before touchdown. During the descent they flew above minimum drag airspeed.

At about 100 feet above the deck they performed a 'pre-flare manoeuvre' which involved pulling the nose up sharply to reduce the glide angle. This put them on the back-side of the drag curve, so they then had to follow this promptly with a progressively higher and higher nose angle (pulling the stick back constantly, and losing airspeed rapidly).

Concorde had an autothrottle: an automatic control linked to the airpeed indicator that *increased* thrust during landing on the back-side of the drag curve to maintain glide angle.

<u>Delta-wing stability</u>

Conventional aircraft often incorporate **dihedral** to keep their wings level: if one wing drops, the aircraft will sideslip towards that wing which will create a higher angle of attack on that wing to lift it back up again.

Deltas don't require dihedral because of a little-known rule-of-thumb discovered by the inventor of the delta-wing Dietrich Küchemann: every five degrees of wing leading-edge sweepback has the same stabilising effect as one degree of dihedral. Again, it's a sideslipping effect.

This rule explains why 'Caret wing' waveriders, which are delta wings with a large negative dihedral angle (known as anhedral or cathedral) are still roll-stable due to their large sweepback angles (see our paper 'Supersonics and waveriding').

So don't give deltas dihedral. Doing so can cause too much roll stability which can cause Dutch-rolling, which is a combined pitch-roll oscillation (different to wibble).

<u>Aerodynamics</u>

One can always resort to the ESDU sheets to get the aerodynamics of delta-wings (see our paper 'Rocketry aerodynamics') however those equations are many and tedious.
A good first guess can be gained by the leading-edge suction analogy derived by NASA for sharp-leading-edged deltas (reference 4).

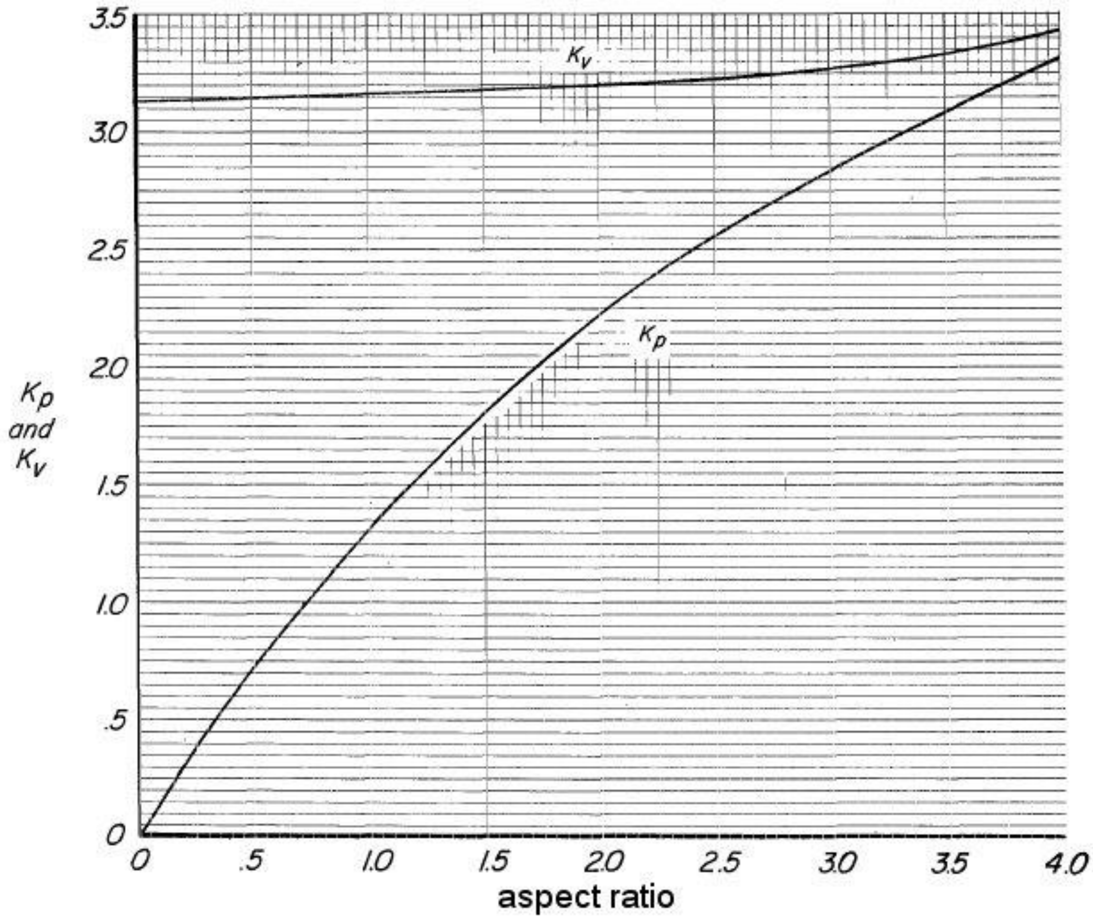
This analogy gives simple, although highly nonlinear, equations:

$$C_L = K_p \sin\alpha\,(\cos\alpha)^2 + K_V \cos\alpha\,(\sin\alpha)^2$$

$$C_{Di} = K_p\,(\sin\alpha)^2 \cos\alpha + K_V(\sin\alpha)^3$$

Where α is angle of attack (up to about 20 degrees) and C_{Di} is the drag coefficient due to lift alone (induced drag).

K_P and K_V are constants that vary with aspect ratio as:



The total drag coefficient is then equal to $C_{Di} + C_{Dp}$ where C_{Dp} is the profile drag coefficient which remains constant (unaffected by angle of attack) and values for it can be looked-up on the web by assuming the wing is just a square flat plate of the same area as the wing **planform area**.

9: wing area

How large should your wings be? Actual size isn't important, but **wing loading** (aircraft weight divided by wing **planform area**) is, as this determines how fast the aircraft has to fly to stay in the air, or to land.

From the **lift equation**, if the aircraft is flying horizontally then the lift is equal to the aircraft's weight and so:

$$W = L = \frac{1}{2}\rho V^2 S C_L$$

The airspeed that the aircraft has to fly at is then: $V^2 = \dfrac{W}{\frac{1}{2}\rho S C_L}$ = wing loading $\dfrac{2}{\rho C_L}$

so the higher the wing loading, the faster the aircraft has to fly.

However, for model aircraft there's also a scale effect: a slow airspeed for a big model will appear to be a fast airspeed for a small model. Two planes with different physical sizes and with the same wing loading will have about the same stall speed, but the smaller one will seem to fly faster and will be more difficult to control, especially during landing.

For instance, the wing loading of a full-scale Cessna 152 is about 500 N/m^2; a model aircraft with such a wing loading would hardly be able to fly.

Typical wing loading with a high **aspect ratio** 1.5 metre **wingspan** model is about 59 N/m^2 This value may be slightly higher with bigger models but should definitely be lower with smaller ones.

A reference that is *not* dependent on the aircraft size is the **cubic wing loading**, which is calculated by dividing the aircraft weight by the wing area raised to the 1.5th power.

Area is length × length, but area to the power 1.5 = length × length × length. Multiplying by this extra length on the denominator (the bottom) of the above fraction takes care of different sizes of aircraft (with different lengths) and their different flying airspeeds (speed = length divided by time).

Different types of aircraft have different cubic wing loadings:

Aircraft type	**Cubic Loading** N/m^3	**Cubic Loading** (kg/m^3 or oz/ft^3)
Sail and Park Flyer	39 to 69	4 to 7
Sport and Trainer	69 to 88	7 to 9
Pylon and Scale	up to 128	up to 13
Electric Ducted Fan	up to 245	up to 25
Space Shuttle (full size)	245	25
Boeing 747 (full size)	324	33
Business jet (full size)	around 373	around 38
Airbus A320 (full size)	564	58

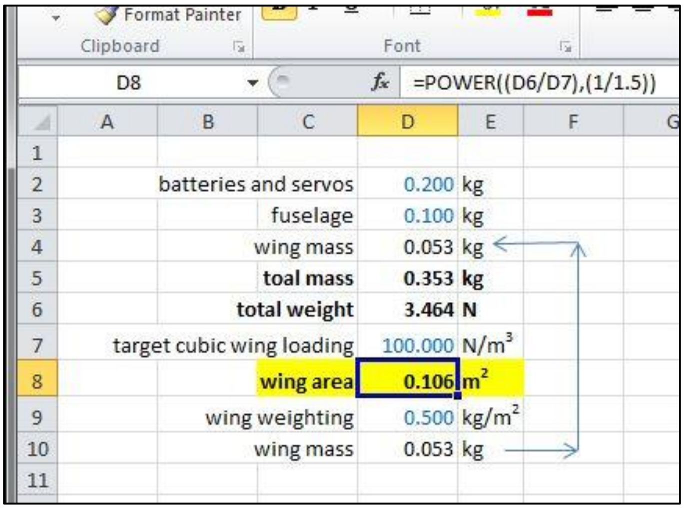
For instance, the full scale Cessna has a cubic loading of about 128 N/m^3 which puts it at the high end of a scale model category regardless of size.

Note that the full size jets have larger cubic loadings; they're optimized to cruise at around 0.8 Mach which requires relatively small wings to reduce lift-induced drag. These small wings would give a horrendously high landing airspeed. Because of this they have special flaps and slats on the wings that not only greatly increase the wing lift upon landing, but also significantly increase the wing area upon landing (so their landing cubic loadings are much less than the above table suggests). But they still land fast.

The Space Shuttle Orbiter had a cubic loading roughly that of a ducted fan radio controlled model, but don't be fooled: its highly swept wings generated only a low lift, so it landed at a high airspeed (200 knots).

Radio control model beginners are advised to choose cubic wing loading values no greater than 78 N/m^3, as this is likely to give relatively low landing speeds.

Achieving your target wing loading is perhaps more of an art than a science, however Microsoft Excel spreadsheets are a good calculation tool. Start with the heaviest masses (batteries, avionics, servos, motor casing) to get a first-cut wing area. Then assign a weighting (kg/m^2) to how much you expect the wing structure to weigh per square metre of wing area and add it to the total mass as shown here:



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D8 | f_x =POWER((D6/D7),(1/1.5))

	A	B	C	D	E	F
1						
2			batteries and servos	0.200	kg	
3			fuselage	0.100	kg	
4			wing mass	0.053	kg	
5			toal mass	0.353	kg	
6			total weight	3.464	N	
7			target cubic wing loading	100.000	N/m^3	
8			wing area	0.106	m^2	
9			wing weighting	0.500	kg/m^2	
10			wing mass	0.053	kg	
11						

This involves a circular calculation. Excel will handle circular references, but you have to switch this ability on by going to the ‘File’ tab (or the ‘Tools’ option in older versions of Excel) then click ‘Options’, and then click ‘Formulas’.

In the ‘Calculation options’ section, select the’ Enable iterative calculation’ check box.
For example, in the above Excel excerpt, the calculated answer for wing mass in cell D10 is fed back into cell D4.

As you can see from the formulas box, the calculation in cell D8 to get wing area is:

$$wing\ area = \left(\frac{total\ weight}{cubic\ wing\ loading}\right)^{\frac{1}{1.5}}$$

10: flight testing

We would like to predict the trajectory of the boost-glider ahead of its first powered flight. Ideally, we could use a wind-tunnel with a force gauge that could give us the lift, drag, and pitching moment (or trim angle) changes with changing airspeed.
Few of us rocketeers have access to a wind-tunnel, but there are ways to effectively do the same thing.

First off, there is the whirling arm: this as the name suggests is simply a long arm that rotates at high rotational speed horizontally. At the end of the arm you mount your model aircraft onto a force gauge; it’s the equivalent of the rocket swing-test.
With today’s wireless electronics and miniature cameras it’s easy to download data from the arm’s sensors into a laptop. The swing arm will give you all the data that a wind-tunnel would, such as the zero-lift angle of attack that is so vital to know for the rocket ascent.

Then there’s the steep hill. If you measure the windspeed accurately, you can obtain a surprising amount of data from glides off of the hill (or dropping your model off of a model aircraft or large kite). Differing amounts of tailplane incidence angle will cause the aircraft to fly at different airspeeds, which you can measure by measuring the time taken to glide various distances. Then you can also plot glide angle versus airspeed to find the best glide speed and plot the drag curve. You can also work out the lift-to-drag ratio (see section 13 later).

Also, there’s a method used by the legendary Burt Rutan early in his career, which we in Scotland used. This is to bolt your aircraft to a car’s roof-rack and get the data through the sunroof. In order to avoid the effects of the disturbed flow around the car itself, you need to mount your aircraft on a tall pylon at least one car roof height above the car.

11: Launching boost-gliders

Getting your boost-glider to altitude can be tricky. We and our friends at STAAR research have devised configurations that have been successful.

Piggy-back

As shown here, the glider is mounted on the back of a conventional booster. Mounting on the nose is possible, but then the glider acts as a canard which can cause static stability problems unless the booster's fins are very large in area.

A clean separation is essential: on the configuration shown above, a catapult on a timed fuse acts on a tow-hook arrangement to pull the glider free just before apogee.
The glider is held in place by slide-rails on the booster during ascent.

The downside of this arrangement is that a lot of noseweight is required in the booster to counteract the rearward mass of the glider.

A-frame

I devised this arrangement to allow me to mount the rocket motors at the rear of the glider (this is me at the 1993 International Rocket Week).

The motors are mounted at the apex of an 'A' shaped frame (the crossbar is just upstream of the nozzle). The legs of the A-frame have T-shaped fins mounted at their ends.

The A-frame and motors separate rearward due to drag at motor burnout.

I've found that it's best to have a higher aspect ratio on the fins than the glider, so that the fins have a steeper **lift curve slope** for added static stability.

It's important to use lightweight materials for the legs of the A-frame to keep the A-frame C.G. forwards.

It's best to arrange the A-frame C.G. to be coincident with the aeroplane aerodynamic centre so that the aeroplane cannot exert a destabilising aerodynamic moment. This generally requires a length of fuselage with noseweight turning the 'A' into an inverted 'Y' with the aeroplane mounted on the side of the fuselage. In the picture above, the aeroplane dominated the mass of the system of aeroplane plus A-frame, so that the A-frame didn't move the system C.G. noticeably rearwards.

With careful placing of the C.G. the fins can be given a negative angle of incidence to give longitudinal dihedral with the glider, and then the whole arrangement of glider plus A-frame flies as one aircraft, allowing horizontal takeoff.

Launch angle
If you're launching a radio-controlled boost-glider just on its own (not piggy-back nor A-frame) then a good launch angle is 45 degrees. This gives you the best chance to correct the trajectory if the glider decides to dive towards the ground, or loop up and back.

Too much power
Consider this: medium-sized HPR solid rockets are capable of hurling a 3 kilogram rocket vertically through the sound barrier. If you fire them horizontally, they're no longer combatting the huge 'force' of gravity, so they'll go a hell of a lot faster.

The boost-glider in the picture above was only powered by three F-class motors, but arced over horizontally and rapidly became just a tiny speck in the distance; it landed badly because I couldn't see its orientation at such a long distance away.

So don't over-power your boost-gliders unless you can get telemetry broadcast back from it, and bear in mind that the high airspeed during the boost phase makes for a very twitchy aircraft: it reacts very fast to the smallest control inputs (consider flying just on the trimmers).

12: Spaceship Two, the ultimate boost glider

First let me say that the following are entirely my own observations and simulations, backed-up by no information whatsoever from the legendary Burt Rutan, designer of Spaceship Two, of whom I am not worthy…

Spaceship Two, like its X-prize winning predecessor Spaceship One, is launched from a carrier aircraft at high altitude (around 50,000 feet).
There are three main reasons for doing this:

Firstly, this is above the thickest regions of the atmosphere, so although SS2 reaches Mach 3 during ascent, it only suffers air-loads equivalent to a moderate subsonic airspeed at sea-level, so the aircraft structure can be lightweight. This also means that the amount of fuel wasted combatting drag during ascent is much less.

Secondly, the rocket is exhausting into lower pressure air, which significantly increases its thrust.

Thirdly, if the rocket engine has to be shut down, then this will occur at high altitude where losing the only engine is a trivial concern, whereas losing an engine on takeoff from a runway is dangerous: not enough height has been reached to find a safe landing area.

After release from its carrier aircraft, SS2 then lights its hybrid rocket engine and pulls-up into a near vertical ascent. Burnout occurs around 50 Km up at around Mach 3, followed by a coast up to an apogee of just over 100 Km.

Re-entry occurs at around 50 Km up at again around Mach 3; drag will have commenced at perhaps 70 Km up, but will be negligible to begin with as the atmosphere's too thin.

Now comes the clever part:
Back in the '90's Aspirespace gave serious thought to entering the X-prize competition, and I was tasked with coming up with a design. As an aeronautical engineer I naturally picked a winged craft: a delta-winged boost-glider powered by a scaled-up version of our hybrid engines.

(To save costs I asked the X-prize organiser Peter Diamandis whether we could launch a one-man vehicle six times instead of a 3-man vehicle twice. Peter chuckled and said no! This one-man craft has evolved into our 'Swift' personal Spaceplane, see our website.)

I reckoned I could get the craft to 100 Km apogee (the competition requirement) but though I racked my brains, I couldn't devise a re-entry strategy that I considered reliable and safe enough for a manned vehicle.

And neither could the other competing teams. Only the genius of Burt Rutan figured it out, and as soon as I saw his simple and elegant re-entry design, I literally slapped my forehead and cursed my stupidity!

The problem was the re-entry gee-loading.
Burt and I had learned from our respective trajectory simulations that the way to keep the gees low was to use a drag device (e.g. a parachute) with as *large* a drag area as possible. This is counter-intuitive: surely a large area will produce large recovery drag and hence high deceleration gees?

At sea-level that would be true, but when falling from apogee into a gradually thickening atmosphere, the larger area can begin the deceleration at much higher altitude. This is because the atmosphere doesn't thicken linearly with decreasing altitude, it increases *exponentially* with decreasing altitude.

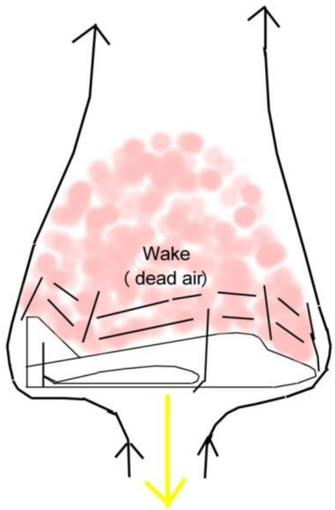
So the *rate* at which the atmosphere is thickening around the craft as it descends at some vertical velocity is much gentler higher up, so if re-entry is performed higher up, then the deceleration to low speed is spread-out over a much larger vertical 'braking' distance, which lowers the gees.

On top of this there's the simple issue that there's less height to fall between 100 Km and the top of the atmosphere compared with 100 Km to the lower atmosphere: you simply haven't built up so much speed.

Burt and I quickly realised that the **planform area** of our delta wings was large enough to act as a drag device, provided we could arrange for the vehicle to belly-flop in (angle of attack of 90 degrees).

I sized my wings to give 3 gees deceleration, while to save weight Burt used smaller wings (higher **wing loading**) to give around 4.5 gees: he's since proved with centrifuges that passengers can comfortably take these gees for short periods.

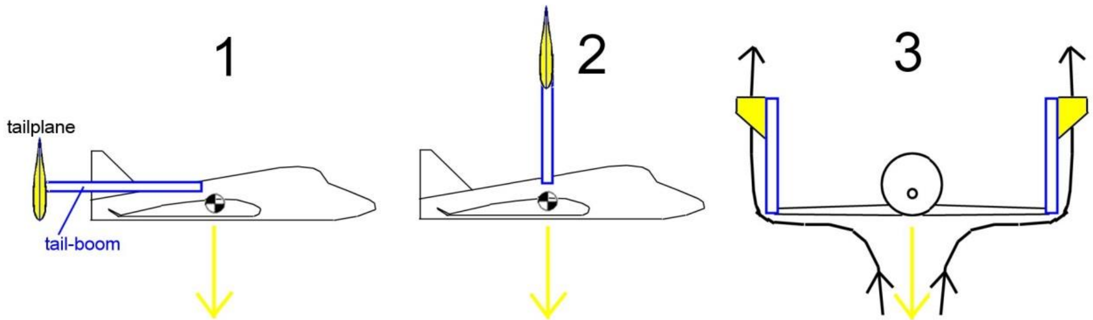
But how could we arrange for the vehicle to hold its belly-flopping attitude?



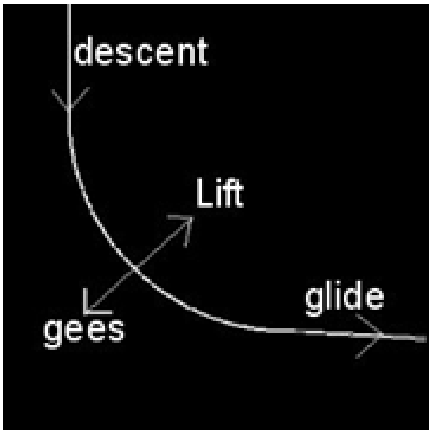
I toyed with stabilising parachutes but there was a problem. The lee of a supersonic vehicle is a large region of dead (unmoving) air. You need a very long rope to get the parachute far enough downstream to avoid this dead wake, and besides, suppose the parachute didn't open?

Next, I wondered whether a tailplane could be made to hold this attitude but again there were problems: the conventional site for a tailplane is on a boom at the rear of the vehicle.

But for a 90 degree angle of attack that just won't work, the tailplane is in the wrong place (picture 1), the tailplane drag will just swing the vehicle around its C.G. It needs to be on a boom aligned with the airflow (picture 2) which would be a pole sticking awkwardly out of the middle of the fuselage.



But this would mean that the tailplane would be in the dead air of the wake; it wouldn't work. At this point I gave up, but Burt didn't. He realised that he could modify the tailboom of picture 2 by splitting it in two and bolting it to the wingtips. As the front view of picture 3 shows, the tailfins are now in the moving air flowing past the vehicle so will function properly. And that's why Burt is a genius!



If you look at these twin tailbooms on the picture of Spaceship 2 on the previous page, you'll notice that they don't swing all the way up to 90 degrees, they stop at about 60 degrees.

There's a reason for that: at some point in the re-entry the craft has to transition from vertical plummet to a near-horizontal glide. Performing this pull-up manoeuvre requires a lot of lift; a delta-wing gives maximum lift (plus a lot of drag) at around 60 degrees angle of attack at supersonic airspeeds.

My design with its larger wings (lower **wing loading**) was to perform this pull-up manoeuvre at a higher altitude than Burt's, which would lessen the gees and extend the glide distance, especially as my design remained supersonic at the end of the pull-up unlike SS2.

Again looking at the picture of SS2 on page 17, notice how the rear of the wings are folded upwards with the tailbooms.

This is done because the centre of pressure of delta-wings moves rearward at very high angle of attack which would make SS2 very nose-heavy.

Instead of somehow moving the entire wing forward to move the centre of pressure forwards again, Burt instead has effectively removed the rear of the wings to move the centre of pressure forward.

Personally, I don't like this concept except insomuch as it's mechanically simple. I reckon that judicious use of fore-aft sliding canards could do the same thing without losing precious drag area during re-entry.

One other cunning aspect of SS2 is that the engine burn duration has been carefully selected so that burnout occurs before the craft has left the atmosphere. This allows standard aerodynamic controls (elevator, aileron, rudder) to be used to control the trajectory right until burnout so that there was no need to design the rocket nozzle to be swivellable, which is a tricky and expensive design for hybrid nozzles.

13: avoiding a power loop

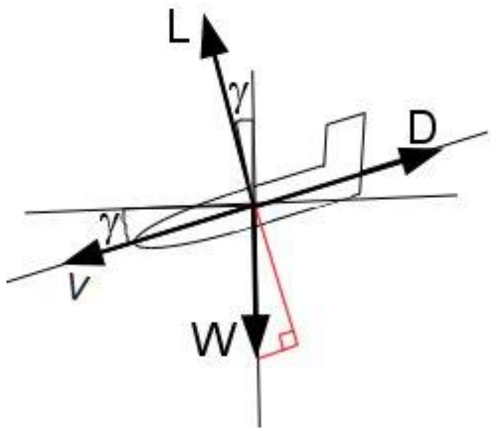
Modern radio control systems allow the inclusion of rate gyros into the control circuit. These tiny solid-state devices can reduce the rate of pitch and roll of an ascending boost glider to give you a better chance of controlling the ascent.

14: The glide equation

During near-vertical ascent, the lift required is near-zero, and the rocket's thrust is combating weight and drag.

Once apogee has been reached, the elevators pop up, and the boost-glider will hopefully enter a steady glide at constant airspeed (constant angle of attack), perhaps with a shallow turn to limit how far it drifts away from the launch area.

The vector diagram for steady, gliding flight is shown here where γ is the glide angle:



The lift L is supporting most of the weight W:

$$L = W\cos\gamma$$

And a component of the weight is counteracting the drag D to maintain the airspeed:

$$D = W\sin\gamma$$

The glide angle γ is then equal to:

$$\tan\gamma = \frac{\sin\gamma}{\cos\gamma} = \frac{\frac{D}{W}}{\frac{L}{W}} = \frac{1}{\left(\frac{L}{D}\right)}$$

$\frac{L}{D}$ is known as the lift-to-drag ratio, which will be a maximum at the minimum drag airspeed, which will then give the shallowest glide angle (maximum horizontal distance covered per loss of height).

Or to put it another way, if your lift-to-drag ratio is four, you'll glide 4 metres forward for every metre of height lost, in still air. This lets you calculate the aircraft's lift-to-drag ratio if you can measure its glide angle (measure its height loss and distance travelled forward).

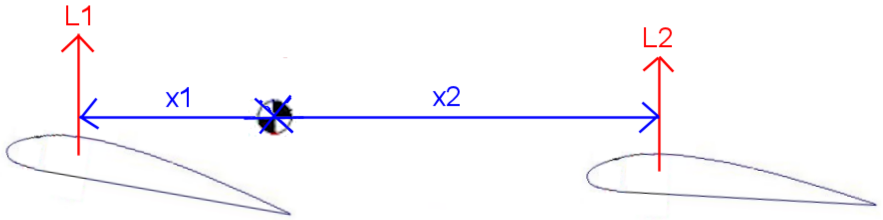
If there is a wind, fly the aircraft against the wind (a headwind) and again measure the distance travelled forward, and also the time of flight.

In still air the aircraft would then have travelled a further horizontal distance equal to the wind speed (metres per second) times the time of flight (seconds). Add this further distance to the actual horizontal distance travelled to calculate the still-air glide angle and hence the lift-to-drag ratio.

15: Longitudinal dihedral

Every model flyer knows that you have to cant the front wing of an aeroplane (canard or wing) at a slightly higher angle than the rear wing (wing or tailplane) otherwise the aeroplane won't keep a steady flying angle and will tumble. This angular difference is known as longitudinal dihedral.

To keep the arithmetic simple, here is an aeroplane with two equally-sized wings, one forward, one aft. (Actually, equal-wing aeroplanes fly badly.) And for simplicity, neither wing has an inherent pitching moment.



The forward wing is bolted-on at double the angle of attack of the rear, so is lifting with double the force of the rear. Therefore the C.G. (pivot of the see-saw) has to be nearer the front wing to keep balance: distance x1 is half of distance x2.

Let's say that the front wing is at an angle of attack of 10 degrees, with the rear wing at 5. x1 is one metre, and x2 is 2 metres.

So taking moments about the C.G: $C_{L\alpha} \times 10 \times 1 - C_{L\alpha} \times 5 \times 2 = 0$
Dividing by lift-curve slope $C_{L\alpha}$: $10 \times 1 - 5 \times 2 = 0$

So the aeroplane is in trim. (The aircraft is in trim when the pitching moment around the C.G. is zero: see next section.)

Now suppose that a gust of wind hits from below and pushes the aeroplane nose-up three degrees.

Now: $(10 + 3) \times 1 - (5 + 3) \times 2 = -3$

The aeroplane is no longer in trim, there's an excess of leverage, which being negative means that the nose will pitch down again (pitch-up is usually taken as positive).

So just by simple arithmetic, having longitudinal dihedral provides an automatic mechanism to restore the flying angle and deal with gusts.

But note: longitudinal dihedral only works if the wings are lifting. If lift is zero, as it has to be on vertical ascent, then the effect vanishes, and you just have to rely on static stability as with any model rocket.

16: Trim

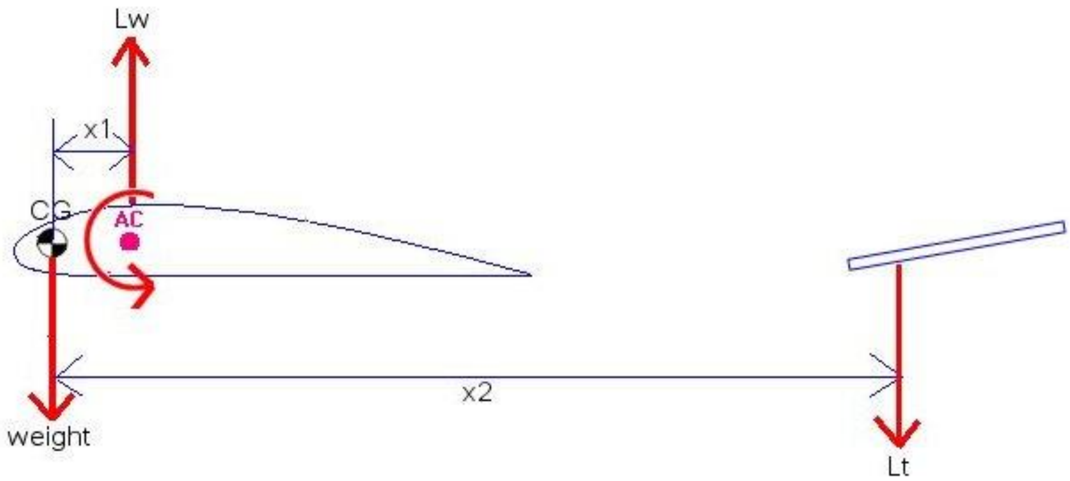
In the previous edition of this paper, I included an onerous derivation of the equation for trim. Perhaps less is more; I shall concentrate on the essential elements of the equation.

The aircraft is in trim when the pitching moment around the C.G. is zero, i.e. when:

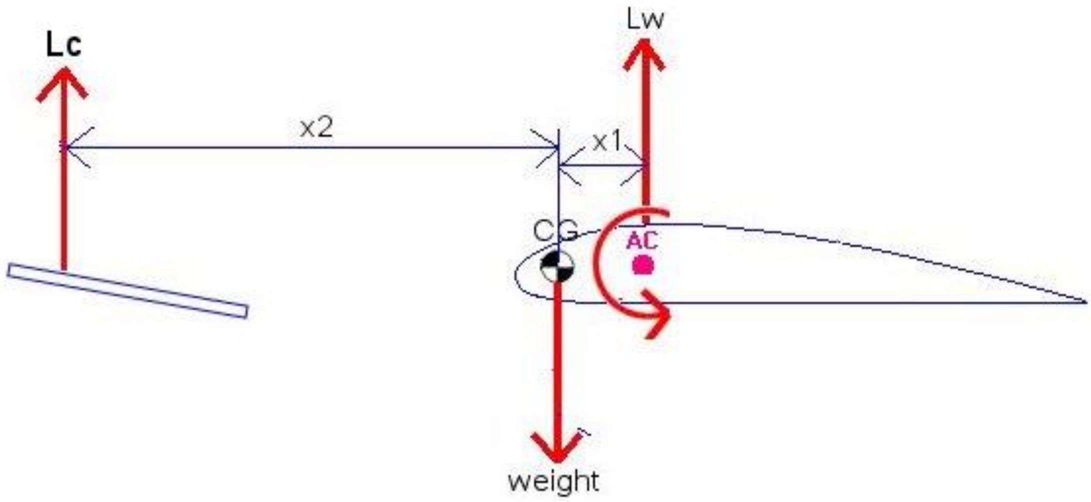
$$M_{CG} = L_w x_1 + M_{AC} + x_2 L_T = 0$$

Where x_1 is the distance between the wing A.C. and the aircraft C.G., M_{AC} is the aerofoil's own pitching moment, x_2 is the distance between the C.G. and the tailplane A.C.
(we ignore the tailplane's own moment, it's small in comparison, and many tailplanes are symmetrical so their own moment is zero). Lw is the lift of the wing, and finally L_T is the downwards lift of the tailplane, so is negative.

[Note that this equation takes nose-down pitch rotation as positive for clarity, whereas nose-up is the more usual positive definition.]



Note that this equation works just as well for canard aircraft, where the lift of the canard L_C is now upward (positive):



Dividing the above equation by **dynamic pressure** ($\frac{1}{2}\rho V^2$) and by Sw, the wing **planform area**, and by $\bar{C}$ which is the mean aerodynamic chord (MAC) of the wing, gives:

$$C_{MCG} = C_{Lw}\frac{x_1}{\bar{C}} + C_{M\_AC} + n_T V_T C_{LT} = 0$$

Where n_T is an efficiency: a correction for the fact that the tailplane is in the lee of the wing and so is in slower-moving air; n_T is therefore less than 1, say around 0.8 (although 1.0 for a canard).

V_T is a collection of terms whose numerator and denominator happen to give units of cubic metres, so for this rather weak reason V_T is called the 'tail volume coefficient':

$$V_T = \frac{S_T x_2}{S_W \bar{C}}$$ where S_T is tailplane **planform area**.

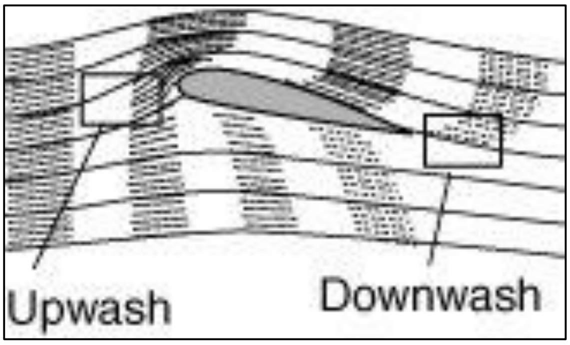
The reason for dividing by $\bar{C}$ is because the moment coefficients C_{MCG} and C_{M_AC} both use $\bar{C}$ as their reference moment arm (i.e. $M_{CG} = \frac{1}{2}\rho V^2 S_w \bar{C} C_{MCG}$).

Now C_{M_AC} is a constant that can be looked-up for the particular wing aerofoil being used (it may vary with angle of attack for deltas).

We need to find what angle to set the tailplane to in order to set $C_{MCG} = 0$
This depends on the tailplane's **lift curve slope**, the tailplane's angle of attack, and the **rigging angles** of both the wing and tailplane.

But unfortunately there are two problems:

1) the airflow just ahead of the wing gets sucked upwards by the wing, creating a flow angle called upwash (unless the wing is supersonic in which case there is zero upwash) and similarly, the airflow downstream of the wing gets deflected downwards, creating downwash.



This upwash affects the canard angle of attack, and the downwash affects the tailplane angle of attack, we need to be able to account for these washes.

The wash angles depend upon the wing angle of attack; we can assume it depends linearly on it i.e:

Upwash or downwash angle $\epsilon = \left(\frac{d\epsilon}{d\alpha}\right)\alpha_W$
Where $\frac{d\epsilon}{d\alpha}$ is the gradient of the wash versus wing angle of attack graph (see reference 6 for typical values).
This modifies the lift of the tailplane to be:

$$C_{LT} = C_{L\alpha T}(\alpha_W - \epsilon) = C_{L\alpha T}\left(\alpha_W - \frac{d\epsilon}{d\alpha}\alpha_W\right) = C_{L\alpha T}\left(1 - \frac{d\epsilon}{d\alpha}\right)\alpha_W$$

Where $C_{L\alpha T} = \frac{dC_{LT}}{d\alpha}$ is the lift-curve slope of the tailplane.

2) The second problem is that the required value of wing lift coefficient C_{LW} changes with airspeed. As the vehicle accelerates (increasing airspeed), less lift coefficient is needed to generate the required lift, therefore less downforce from the tailplane is needed to trim.

Fortunately, on a completely vertical ascent, no lift is required, so C_{LW} remains constant at zero.
Furthermore, if both the wing and tailplane are symmetrical (zero camber), then their angles of attack should remain zero for trim whatever the airspeed on a vertical ascent.

Tail-less deltas
What if there is no tailplane or canard, i.e. just a pure delta-wing? Well we can still use the above equation, though now we want the required upward deflection of the elevator to trim. Note that the angles of attack of the wing and elevator are now equal (no wash terms), but x_2 is now the distance from the C.G. to the elevator.

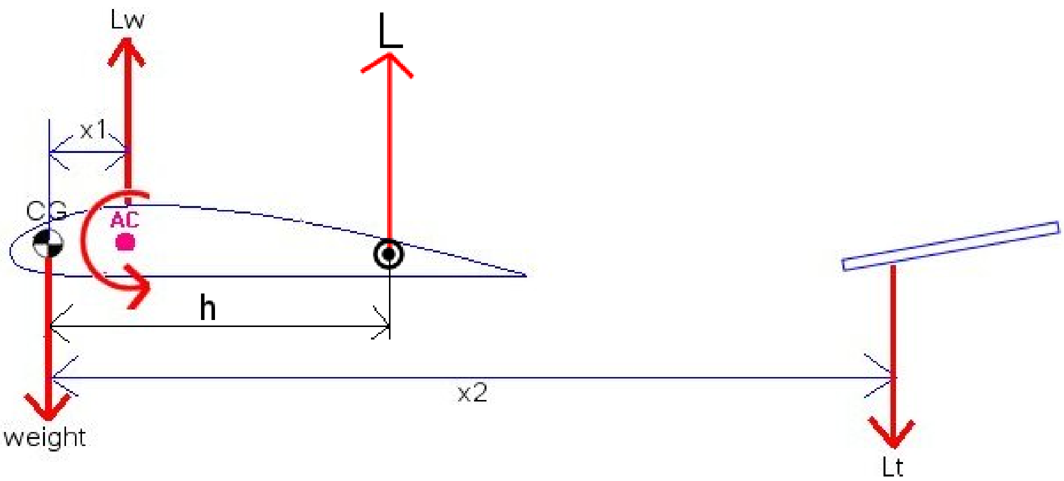
Now the elevator is a part of the wing, and so it's within the airflow around the wing. This means that the downward lift of the elevator with elevator deflection is difficult to calculate, you'd be better to look it up on the web, or measure it directly on a scale model.

17: Static stability

Using the above trim equation, we can now assess the static stability (Static margin) of the aeroplane.

If a gust causes a small change ($d\alpha$) in angle of attack, then an aerodynamic moment (dC_{MCG}) must be created about the C.G. that reduces this angle of attack, or mathematically, that:

$$\frac{dC_{MCG}}{d\alpha} < 0$$



Recalling the above trim equation:

$$M_{CG} = L_W x_1 + M_{AC} + x_2 L_T = 0$$

Now we can also define the moment about the C.G. in terms of the total lift *L* of wings plus tailplane acting at the Neutral Point which is distance *h* (the Static margin) from the C.G:

$$M_{CG} = hL + M_{AC} = h(L_W + L_T) + M_{AC}$$

So: $L_w x_1 + M_{AC} + x_2 L_T = h(L_W + L_T) + M_{AC}$

or cancelling: $L_w x_1 + x_2 L_T = h(L_W + L_T)$

Dividing gives an expression for *h*:

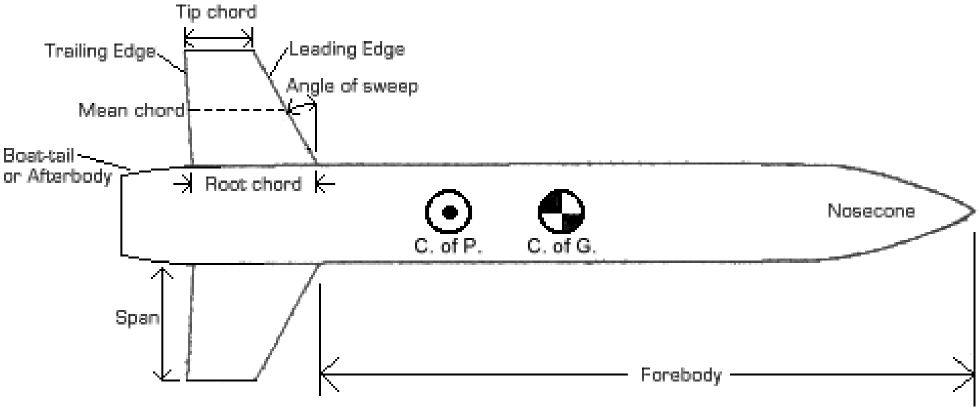
$$h = \frac{L_W x_1 + L_t x_2}{L_W + L_t}$$

Dividing this equation by **dynamic pressure** ($\frac{1}{2}\rho V^2$) and by *Sw*, the wing **planform area**, gives:

$$h = \left(\frac{x_1 C_{LW} + \bar{C} n_T V_T C_{LT}}{C_{LW} + \left(\frac{S_T}{S_W}\right) n_T C_{LT}} \right)$$

Glossary:

Geometric definitions:



(strictly, the forebody is everything upstream of the boat-tail when there are no fins present.)

Angle of attack: α
This is usually referred to as 'alpha', and corresponds to the angle between the incoming airflow direction (usually the **Freestream** direction) and some vehicle or fin datum such as the wing chord line.

Angle of incidence (referred to as 'rigging angle' in the U.K.):
The fore-aft tilt of the wings or tailplane with respect to the aircraft's fuselage centreline.

Aspect ratio AR:
A wing or fin's wingspan divided by its width (or mean chord, see above **geometric definitions** diagram.)

Bernoulii's principle:
Is just a statement of the Law of Conservation of Energy couched in aerodynamic terms (see **Dynamic Pressure**) and is expressed in the equation: $P + \frac{1}{2}\rho V^2$ = constant,

or: $\Delta P = -\frac{1}{2}\rho \Delta V^2$ where P is pressure, ρ is density, and V is flow velocity.

Calibres, Calibers:
In rocketry, vehicle dimensions are usually divided by (compared to) the diameter of the thickest part of the fuselage so that rockets of different size can be compared: this diameter is therefore one Calibre.

Canard:
Ducks (in French 'Canards') have very long necks: their wings therefore appear to be very rearwardly placed. A Canard aircraft has rearward main wings, plus a small forward wing which does the trimming by lifting the nose up.

Centre of Gravity, centre of mass (CG):
The point within the vehicle that is the centroid of mass, the balance point.

Centre of Pressure (CP):
The point on the rocket's surface where the average of all the aerodynamic pressure forces from the nose, body, and fins act. This must be behind the Centre of Gravity (CG) by at least one **Calibre** for stability.

Cubic wing loading (see **wing loading**):
Wing loading taking aircraft physical size into account, calculated by dividing the aircraft weight by the **wing planform area** raised to the 1.5 power and so has units of N/m^3

$$cubic\ wing\ loading = \frac{W}{S^{1.5}}$$

Dihedral:
A shallow angling of the wings as seen in front view, which means that the wing tips are physically higher than the wing roots.

Drag (equation):
Drag, or 'air resistance', is the retarding force experienced by bodies travelling through a fliud (gas or liquid).
The equation used to calculate drag is simply the *drag coefficient, Cd*, times **dynamic pressure**, times some reference area '*S*', i.e: (ρ = atmospheric density.)
For the rocket vehicle, this reference area 'S' is the maximum cross-sectional area of the fuselage (ignoring the fins or small, local structures), whereas for aircraft, it's the total wing area.

Drag curve (drag polar):
The graph of drag versus airspeed.

Dynamic pressure: (q)
All aerodynamic forces scale directly with the kinetic energy term: $\frac{1}{2}\rho V^2$
ρ being volume-specific mass or air density, and *V* = flow velocity.
This kinetic energy term is called Dynamic Pressure (q), to distinguish it from its Potential energy counterpart of static pressure (P).

Forebody:
The nosecone and forward fuselage.

Freestream:
The undisturbed airflow ahead of the vehicle.

Lift curve:
The graph of lift coefficient versus angle of attack.

Lift curve slope:
The gradient of the lift versus angle of attack graph.

Lift (equation):
Lift is a force generated by aircraft at right-angles to their flightpath.
The equation used to calculate lift is simply the *lift coefficient, Cl*, times **dynamic pressure**, times some reference area '*S*', i.e: $L = \frac{1}{2}\rho V^2 S\ Cl$ (ρ = atmospheric density.)
For aircraft, this reference area 'S' is the total wing area.

Mach number:
The vehicle's airspeed *V* (or the **local** airspeed around a nose or fin) compared to the speed of sound '*a*':

$$M = \frac{V}{a}$$

Pitching moment coefficient: Cm
The lift force of the fins and nosecone (and boattail) causes a torque that rotates the vehicle. In stability analyses we usually require to calculate the torque about a fictitious pivot at the nosecone tip.

The coefficient is: $Cm = \frac{T}{\frac{1}{2}\rho V^2 d}$ where *T* is the torque and *d* is fuselage (max) diameter.

Planform area:
The area of a two-dimensional drawing of the vehicle (or its wings) as seen from above.

Reference area: (S)
See Drag (equation)

Rigging angle: see **angle of incidence**

Skin:
The outer covering or surface of the vehicle.

Subsonic:
Vehicle airspeed is below Mach 1 (see **Mach number**).

Supersonic:
Vehicle airspeed is above Mach 1 (see **Mach number**).

Taper ratio:
The ratio of fin tip chord divided by fin root chord (see above diagram 'geometric definitions').

Transonic:
Above a **freestream Mach number** of about 0.7, certain parts of the **local** flow around the nose and fins will hit a local Mach of above 1.0, **supersonic**.
Similarly, up to a freestream Mach number of about 1.4, certain parts of the local flow around the nose and boat-tail are still **subsonic**.
The transonic zone is this freestream Mach number region where there is a mix of subsonic and supersonic flow. This mixture makes predicting the aerodynamics of the zone difficult and inexact.

Vehicle: (the)
A stationary object immersed in a moving airflow, or an object moving through stationary air. (Aerodynamically, these two situations are identical in every respect.)
Here, the vehicle is a rocket-vehicle.

Wing loading:
Is the weight of the aircraft (assuming 1 gee) divided by its wing **planform area** and so has units of N/m^2

References:

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