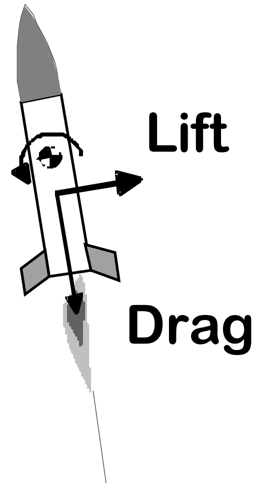
Basic Rocketry Aerodynamics

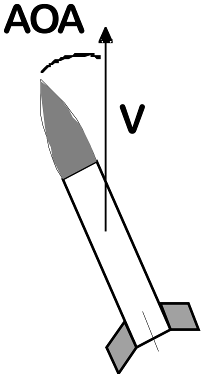
What basic aerodynamic forces affect a rocket's flight?
The basic aerodynamic forces that affect a rocket's flight are drag and lift. Drag negatively affects a rocket's acceleration, velocity and ultimate altitude. It must be minimized. Lift causes directional changes in a rocket's flight that can be used to stabilize a rocket's direction of flight.

What is drag?
Drag is a component of aerodynamic force acting directly against a rocket’s velocity by virtue of the rocket’s motion through surrounding air. Drag acts as a brake on a rocket’s motion.



What is lift?
Lift is a component of aerodynamic force acting perpendicular to a rocket’s velocity with respect to surrounding air. The lift causes a rocket to pitch (pivot) around its center of gravity.

What is AOA?
AOA stands for Angle Of Attack. The angle of attack is the angle between a rocket’s velocity vector and its centerline.



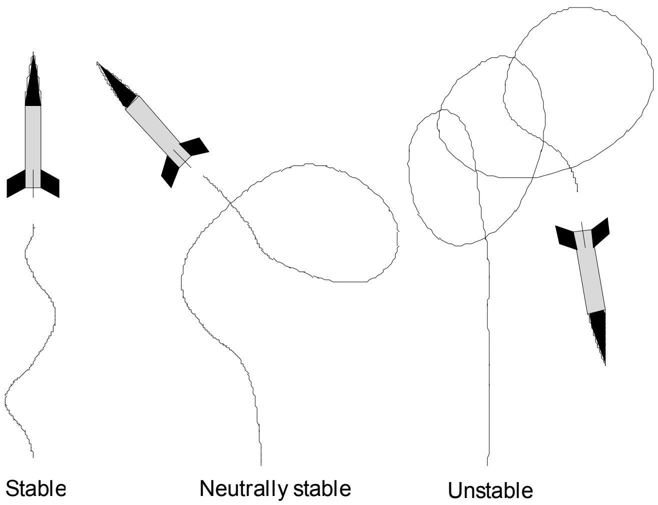
What is stability?
Stability is a name given to how a rocket behaves when flying at various angles of attack (AOA). A rocket can either be stable, unstable or be neutrally stable:

<u>1. Rocket is stable:</u>
- If when flying at an AOA a pitching movement occurs on the rocket’s airframe that reduces the AOA. This self corrects errant flight.

<u>2. Rocket is unstable:</u>
- If when flying at an AOA a pitching movement occurs on the rocket’s airframe that increases the AOA. This makes errant flight worse.

<u>3. Rocket is neutrally stable:</u>
- If flying at an AOA does not create any pitching movement on the rocket’s airframe. This has no effect on errant flight. The result is total unpredictability.

In other words:
A stable rocket will automatically steer away any unwanted AOA. Its flight path may be predicted by trajectory calculation.



If the rocket is not stable however, its flight path will be unpredictable. Unstable rockets will "try to fly backwards", entering a fierce spinning movement in which they are prone to break up.

Neutrally stable rockets may turn and fly in any direction whatsoever without warning.

Important Aerodynamic Quantities

Mach number

In dealing with rocketry aerodynamics one must apply fluid dynamics (air is a viscous fluid) to the problem. In fluid dynamics, velocity in absolute terms is virtually unimportant. Instead, the behavior of fluids depends on a handful of dimensionless velocity measures, one of them being the Mach number.

The Mach velocity refers to the speed of sound in the fluid, and varies with the temperature. For dry air we may write:

$$c = 20.055\sqrt{T}$$

Where: c is the speed of sound in m/s; and T is temperature in Kelvin.

Then Mach number is the velocity normalized to the speed of sound:

$$M = {}^{v}\!/_{c}$$

Reynolds number

As with the Mach number, the Reynolds number is a dimensionless measure of velocity. It is primarily used for determining whether the flow is laminar (smooth and coherent over a surface) or turbulent (disrupted and disorganized over a surface) which then allows for an estimation of skin friction.

For a rocket of length L, flying at velocity v in air of density ρ, the Reynolds number is:

$$\mathrm{Re} = \frac{vL\rho}{\mu}$$

The quantity μ is the dynamic viscosity of the air. Some representative values of ρ and μ are:

$\mu = 1.8*10^{-5}$ kg/(ms)

$\rho = 1.2$ kg/m^3

Reynolds numbers easily gets quite large - in the range of 10^5 - 10^8.

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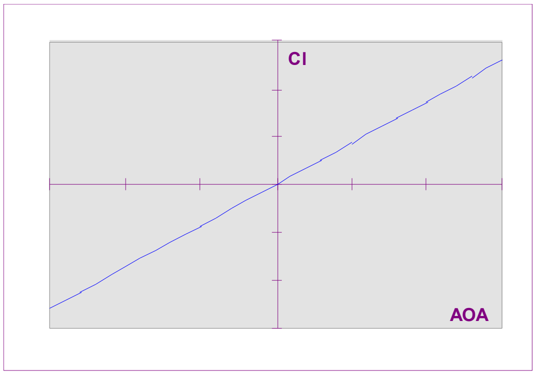
Coefficients of lift and drag

For a rocket traveling at velocity v, in air with density ρ, the aerodynamic forces may be written as:

$$Lift = \tfrac{1}{2} A\rho C l v^2$$

$$Drag = \tfrac{1}{2} A\rho C d v^2$$

The properties Cl and Cd are the coefficients of lift and drag. The property A is a reference area. A is coupled to Cl and Cd in the following way: A might be chosen at random, but Cl and Cd scale accordingly. Most commonly, A is chosen to be the largest cross sectional area of a given rocket body.



For small angles of attack, the lift coefficient (Cl) is proportional to AOA. For a symmetrical rocket, Cl is zero at zero AOA. Under such circumstances, the lift coefficient itself partly looses its meaning. Instead, the slope of the Cl versus AOA curve becomes the property of interest. This is often referred to as *the lift curve slope coefficient*.

What this means is that for a stable rocket flying straight and true, the AOA is zero and the Cl is zero. The rocket should then continue in its straight and true path. If, for whatever reason, the AOA should change to an angle other than zero then the Cl will also increase and thereby tend to force the rocket back to the intended flight path.

Center of Pressure - CP.

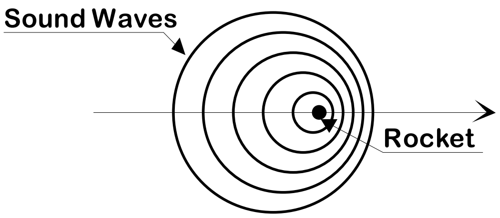
The center of pressure is the position where the resulting aerodynamic lift acts on a rocket's airframe. The position of CP depends on the distribution of lift on the rocket. Normally the fins generate the major part of lift, thus for rockets with only one set of fins; the CP is generally located in the vicinity of the fins.

Subsonic and supersonic velocities

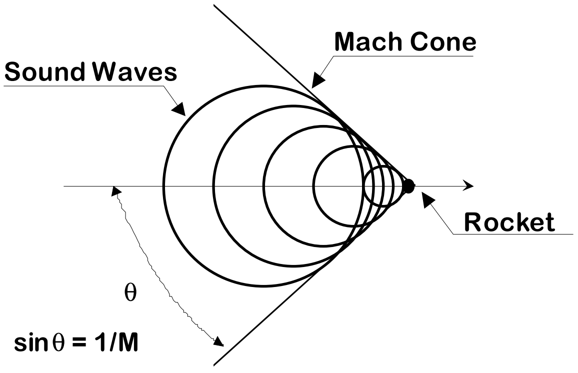
When a rocket travels through the air, the flow around it depends on the rockets velocity with respect to the velocity of pressure distortions in the air. Pressure distortions are percieved as "sound", hence the the flow field depends on the rockets velocity with respect to the speed of sound (ie. its Mach number).

The movement of the rocket through the air, creates sound waves. As the sound travels at the same speed in every direction, the emitted sound will generate a spherical wavefront, analogous to the circular wave created by interrupting a calm water surface in a single point. If the rocket travels at a speed less than the speed of sound, the sound waves are able to escape the rocket, and it emits sound like any other object we are used to. However, if the rocket travels faster than the speed of sound, the sound waves does not escape from the rocket in the usual maner. Instead, they add up to form a wavefront of conical shape with the rocket in its vertex. This conical wavefront is often reffered to as the *Mach cone*. Note, that this is analogous to the "V" shaped wavefront generated by a ship, that travels across a water surface. The faster the rocket travels, the sharper Mach cone.

The Mach cone explanes why a supersonic object generates a *sonic boom*: all the acoustic energy is compressed into one single wavefront. Anyone who are hit by the Mach cone will percieve a short spike of noise - the sonic boom. The Mach cone also explains, that those who stays in the viscinity of the launch tower when a supersonic rocket is launched will not hear any sonic boom - they are at the inside of the Mach cone, and are never hit by the wavefront.



Rocket at subsonic speed



Rocket at supersonic speed

Speeds lower than the speed of sound (M < 1) are said to be *subsonic* - speeds higher than the speed of sound (M > 1) are said to be *supersonic*. The flowpatterns of subsonic and supersonic speeds are fundamentally different, however also within the subsonic or supersonic regions there are subregions of different flow behavior.

At low subsonic speeds, the air has plenty of time to adapt to the rocket and generates a nice flow around the rocket without any pressure build-up. This is the case for speeds roughly up to half the speed of sound, and the flow is said to be *incompressible*. When the speed of the rocket gets higher than roughly half the speed of sound, the air has no longer time for creating ideal flow patterns. Instead the air in front of the rocket starts to compress, and the coefficients of lift and drag increases (basically with a factor of $1/\sqrt{1-M^2}$) from their incompressible values. This is the region of subsonic compressible flow.

As the air cannot move straight through the rocket, it has to move around it instead. Basically it does that by slowing down and changing direction to get by the nosecone, accelerate to get past the rocket body, and then again slowing down and changing direction for getting by the base of the rocket. This means, that the speed of the air around the rocket is somewhere higher and somewhere lower than the speed of the rocket with respect to the undisturbed air. For this reason, the airflow can be partially subsonic and partially supersonic if the rocket flies at high subsonic speeds (roughly 0.8M or higher) or at low supersonic speeds (roughly 1.2M or lower). This is known as the *transonic* speed region. The actual limits of the transonic region depends on the shape of the rocket. For most rockets, the coefficients of lift and drag reaches their maximum in the transonic speed range.

In the supersonic speed region, the coefficients of lift and drag decreases (basically with a factor of $1/\sqrt{M^2-1}$) from their maximum, but at high supersonic speeds they approach some constant nonzero values. At high supersonic speeds, the air simply has no time to move away from the rocket, and it starts to act more like a bunch of independent air molecules. High supersonic speeds are said to be hypersonic. Again the actual limit for hypersonic flow depends on the shape of the rocket, but as a rule of thumb, hypersonic conditions begin at five times the speed of sound.

Practical considerations

How do I check my rocket's aerodynamic stability?

You need to determine the position of CP for the rocket and its center of gravity (CG) at any condition throughout the rocket's flight. CP is the resulting point on the rocket, where the lift forces act. CG is the weight balancing point of the rocket. If CG is located forward of CP, then the rocket is stable.

Note that CG and CP are not fixed in their locations but generally move with varying conditions. CG moves as propellant is consumed whereas CP moves with the velocity of the rocket and its AOA.

How do I determine the location of CP?

For rockets flying at low speeds - less than approximately 180m/s (600fps), two methods are applicable: The method of Barrowman and the cardboard cutout method. The method of Barrowman estimates the lift and center of pressure for every major part of the rocket and combines them to values applicable for the complete rocket. In the cardboard cutout method, a silhouette of the rocket is cut in cardboard, and its weight balancing point is determined. The cardboard cutout method gives a rough estimate for the CP at 90 deg. AOA. The method of Barrowman estimates CP at 0 deg. AOA. As rockets normally fly at AOA of less than 10 deg., the method of Barrowman is normally more consistent with reality. One or both methods are commonly implemented in rocketry software packages, such as:

- VCP
- RocketCAD
- RockSim
- Aerolab
- Rogers Aeroscience Software (not shareware)

For rockets flying at speed higher than 180m/s (600fps) calculation of CP gets rather complicated, and high speed CP calculation is not yet commonly included in rocketry software. In general, rockets that are stable at low speeds will be stable until velocity gets in the range of Mach 2 - however, rockets with fins with high thickness ratios might exhibit stability problems in the transonic speed range (0.8-1.2 Mach).

The position of CP is also affected by angle of attack, commonly CP moves forward with increasing AOA. If the rocket leaves its ramp at low speed in high winds, the resulting AOA might be considerable and cause the rocket to be unstable.

Rocket movement further affects the position of CP. Pitching and rolling movements induce additional velocity components around the different parts of the rocket. The induced velocities vary with distance from CG and cause the different parts of the rocket to fly at different AOA, thus affecting the position of CP.

In brief - the method of Barrowman
The most common method for determination of CP among model, High Power and amateur rocketeers is the method of Barrowman. The method is based on scientific works, but is greatly simplified in a way that makes it suitable for amateurs. It requires no more than a pocket calculator, and college level mathematical skills.

In order to keep the method simple; Barrowmann makes some basic assumptions:

1. The angle of attack is small - less than app. 10^{O}
2. The velocity of the rocket is less than 180 m/s (600 fps).
3. The airflow around the rocket is smooth with no abrupt directional changes.
4. The length of the rocket is significantly larger than its diameter.
5. The rocket body is pointed.
6. The rocket body is symmetrical around its centerline.
7. The rocket body is stiff, so that all parts of the rocket flies at the same AOA.
8. The fins are made from thin plates..

Barrowman divides a rocket into standard components - nosecones - fins - conical transitions - and indirectly: cylindrical body tubes. For each component, he has established simple expressions for the lift curve slope coefficient and the center of pressure for that particular type of component. By combining theese, the resulting position of CP is easily calculated. According to the assumptions, the AOA is unimportant, as it is the same for all components of the rocket.

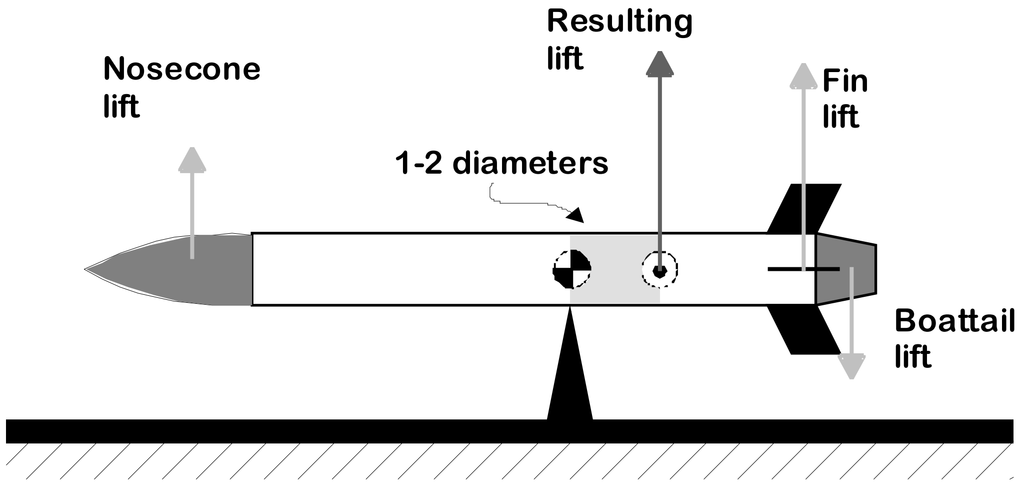
How do I determine the location of CG?
The best way of finding the center of gravity is simply by keeping track of the weight and center of gravity for every single component of the rocket. The resulting CG is then determined by a moment analysis - Actually, some rocketry software like:

- VCP
- RockSim
- Aerolab

will do the CG calculation for You.

Finally, the location shoul be verified by finding the weight balancing point of the actual rocket - both with a fully loaded motor and with an empty motor.

Is there an optimum relationship between Cp and Cg?
Yes, it is the Static Stability Margin. The Static Stability Margin is defined as the ratio of the distance between CP and CG to the maximum body diameter of the rocket. As a rule of thumb, the static stability margin should be between 1 and 2. If the static stability margin is too small, the stability of the rocket could be in danger, especially at low velocities. If static stability is too large, the rocket will be more sensitive to the wind. Also the forces acting on the rocket in terms of lift and drag will be greater, increasing drag and mechanical stress on the fins.



Stability design considerations

Fins on rockets primarily generate lift. The nosecone, shoulders and boattails on rockets also generate lift. While fins, nosecone and forward facing shoulders generate lift in one direction, boattails generate lift in the opposite direction - in stability considerations, one might say that boattails generate negative lift.

If there are more than one set of fins, the most forward set of fins interrupt the airflow around the fins behind them. This reduces their lift, thus reducing the stability of the rocket. Warning, this effect is NOT covered by the Barrowman or cardboard cutout methods of determining Cp.

Practical rules

When designing an airframe:

1) Place the fins as far away from nosecone as possible.

2) Use only one set of fins if possible. Otherwise, make the most aft set of fins larger than indicated by Barrowman analysis.

3) Do not use a boattail without increasing fin size accordingly.

4) On multistage rockets, make sure that the rocket is stable in any of its configurations during flight.

It's worth noting that we can do any "worst combo" of breaking the rules if the design equations say that it will fly correctly. The math is king of this hill, and the practical rules can be violated and the rocket will be stable - if it is so designed.

Aerodynamic drag

The drag of a rocket depends on velocity (in terms of Mach and Reynolds numbers) and of the angle of attack.

The drag of a rocket is basically generated by 3 different mechanisms:

- skin friction

- pressure drag
- base drag.

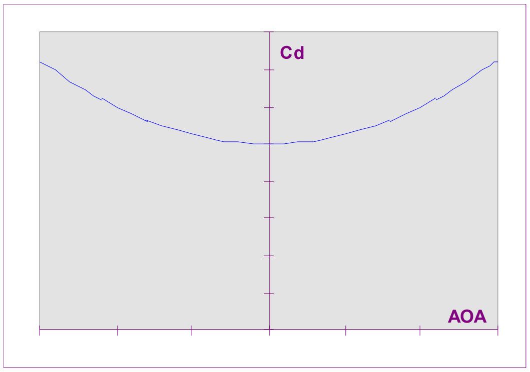
Skin friction is not really friction between the rocket and the surrounding air, but rather friction between air molecules moving at different speeds in the boundary layer that surrounds the rocket. This effect is coupled to the overall surface area of the rocket. At subsonic speeds, skin friction is normally the largest contributor to overall drag, and even at supersonic speeds, it is a main contributor.

Pressure drag is the drag caused by a rocket "pushing the air in front of it aside". At subsonic speeds, pressure drag normally contributes only slightly to the overall drag. At supersonic speeds, pressure drag (then commonly named wave drag) can be significant, especially if the forward facing parts of a rocket are blunt.

Base drag is created by the wake trailing behind a rocket. During powered flight, base drag is significantly reduced as the wake tends to get filled by the exhaust from the motor. One common way to reduce base drag is the use of a boattail that makes the rearmost cross sectional area smaller than the cross sectional area of the main rocket body. The drawbacks of boattails are that they tend to increase wave drag at high velocity and reduce stability of a rocket due to their "negative" lift.

The coefficient of drag is affected by the angle of attack. At small values of AOA, the drag coefficient may be written as:

$$Cd = Cd_0 + const.(AOA)^2$$



Drag design considerations

Optimal design in terms of minimum drag depends heavily on the velocity in question. No design is generally optimal for all velocities encountered.

For rockets spending most of their flight at subsonic speeds, the nosecones should be rounded and they should have boattails. Similarly, the leading edges of the fins should be rounded and have sharp trailing edges. Maximum fin thickness should be closer to the leading edge, than to the trailing edge.

For rockets spending most of their flight at supersonic velocities it is essential that all forward facing surfaces, i.e. nosecone and leading edges, are sharp. Boattailing and sharp trailing edges are also desirable. The fins should be thin with maximum thickness midway between leading and trailing edges.

Rockets that reaches transonic speeds might benefit from what is called *the area rule:* For slender bodies - like most rockets - it turns out, that the transonic pressure drag does not really depend on the actual shape of the body (ie. diameter versus length), but rather on its distribution of cross sectional area (ie. cross sectional area versus length). The practical consequence of this is, that when adding a set of fins to a rocket body, increase of the rockets pressure drag can be avoided by reducing the rocket body diameter where the fins are attached, so that the cross sectional area is unchanged.

In general, the total surface area of any rocket should be kept as small as possible. Also, the cross-sectional area should be kept at its minimal practical value. Making a rocket very fat or very long is undesireable.

When drag considerations contradict stability considerations, then stability conditions are of greater importance.

Some rocketry software predicts the coefficient of drag for rockets, such as:

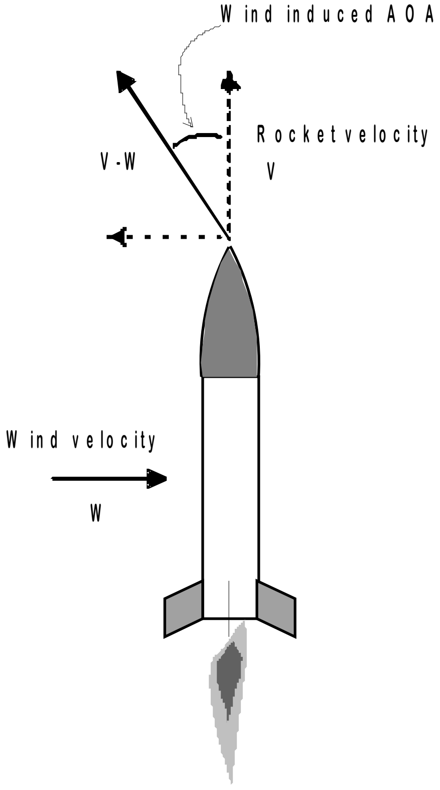
- Rocdrag
- Aerolab
- RockSim (maybe no the demo version)
- Rogers Aeroscience Software (not shareware)

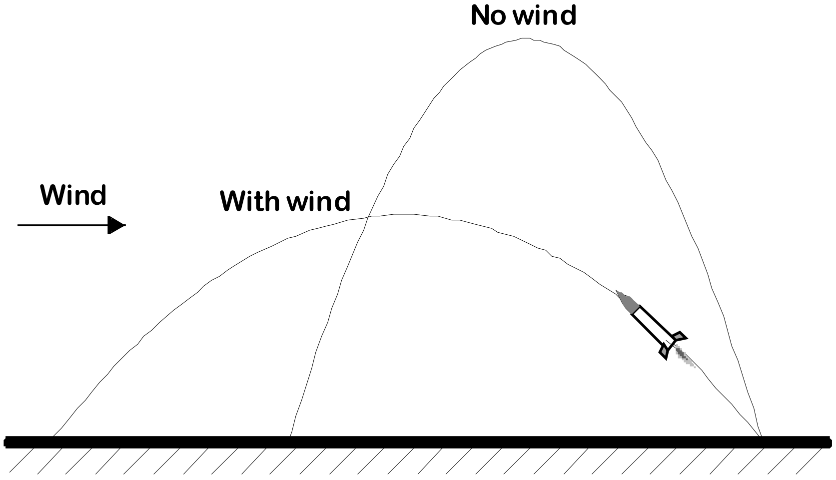
Wind effects on trajectory

The launching of rockets should never be done under high wind conditions. Basically wind affects a rocket's flight in two ways: stability and "weathercocking".

When a rocket leaves the ramp, its horizontal velocity with respect to the surrounding air is the rocket's horizontal velocity at no wind conditions minus the wind velocity.

If the rockets vertical velocity is not significantly larger than the wind velocity, the rocket will be exposed to a wind induced angle of attack which may be substantially larger than the 10 degrees covered by common Barrowman stability analysis. The CP might then moves forward of it's designed position and thus render an otherwise stable rocket unstable or neutrally stable. These conditions may be avoided by awaiting calmer conditions.
If, on the other hand, the rocket stays stable under windy conditions, it will start to pivot against the wind to eliminate the wind induced AOA. This effect is commonly known as *weathercocking*.





If the rocket pivot against the wind while the motor is burning, the rocket will then accelerate in the new direction. The net result is that the rocket simply turns in the direction against the wind, and the trajectory will be flatter than expected. It should be noted that trajectory is affected only when the rocket accelerates while under influence by the wind: When the rocket gains velocity, trajecory gets flatter, and when the rocket looses velocity trajectory gets steeper. However, the acceleration during powered flight is dominant, making a flatter trajectory the net result of the wind influence.

After burnout, the trajectory is practically unaffected by the wind. However, stability might still be in danger. It is sometimes observed that a rocket gets unstable at apogee due to the wind.

Guidelines

Design for stability
Stability is a necessary condition for successful flight. Unstable rockets are failures, and may even be dangerous. Keep the design simple, with no unnecessary fins or transitions. Place the fins only at the aft end of the rocket. Make the fins thin - but do not underestimate the forces that act on them - they should be made from strong materials and thoroughly attached to the rocket body.

Check the Static Stability Margin
Check the CG for the rocket with and without propellant by a simple balancing procedure. Easy to do, and it may save You from disappointment. Use some of the suggested programs to determine the rocket's Cp. Make sure, that CG is between one and two rocket diameters forward of CP under ANY condition during flight - rather more than less.

Design for performance
If it does not conflict with your stability precautions, design for low drag. Low drag means high performance. Make the fins thin, and not too large. Make the rocket body slender, but not too long. As a rule of thumb, the rocket body should be between 10 and 20 times the diameter. For supersonic flying rockets, a sharp pointed nose and sharp leading and trailing edges on the fins are preferable. Keep the overall surface down.

Avoid high winds
Never launch a rocket in high winds, and never launch it vertically. Instead, launch it at an 85 deg. elevation directly against the wind. If the rocket weathercocks, then you will know precisely in what direction it will fly. The trajectory may be longer and flatter than expected,

but if the rocket carries a recovery system, the same wind will make it drift straight back towards you, thus saving you from a long walk.

Always think safety
Safety first, not only for yourself, but also for the surroundings. Plan everything in detail before actually setting up a launch.

Note on software:
The suggested software for stability and drag analysis are meant as examples only. There might exist other excellent software for the same purposes.

Suggested literature in the field of rocketry aerodynamics:

Fluid Dynamic Drag
S. F. Hoerner
Hoerner Fluid Dynamics 1965

Boundary Layer Theory
Dr. H Schlichting
McGraw-Hill

Mechanics of Fluids
W. J. Duncan, A .S Thom, A. D. Young
Edward Arnold

Missile Configuration Design
S. S. Chin
McGraw-Hill 1961

Theory of Wing Sections
Ira h. Abbot, A. E. Von Doenhoff
Dover Publications, Inc 1958

USAF Stability and control DATCOM
Flight Control Division
Air Force Flight Dynamics Laboratory
Wright-Patterson Air Force Base, Ohio
1978