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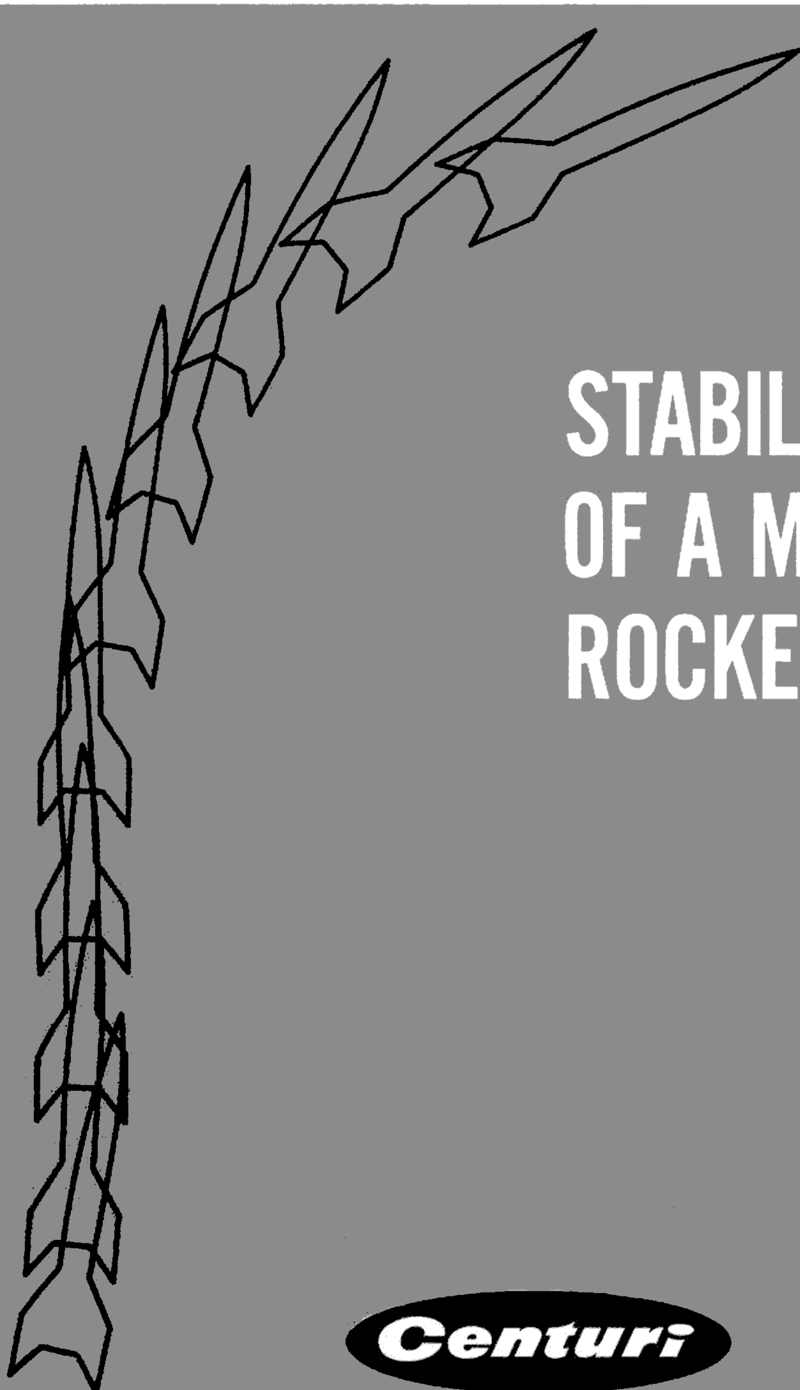
TECHNICAL INFORMATION REPORT



STABILITY OF A MODEL ROCKET IN FLIGHT

Centuri

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TECHNICAL INFORMATION REPORT 30

STABILITY OF A MODEL ROCKET IN FLIGHT

BY JIM BARROWMAN

This report has been written to help you understand the scientific principles that affect the stability of your model rockets. It is not a "how to" manual on calculating stability. It has been written on the assumption that every model rocketeer wants to know "why" as well as "how to".

The best technique for accurately determining the stability of model rockets is given in CENTURI'S TIR # 33.

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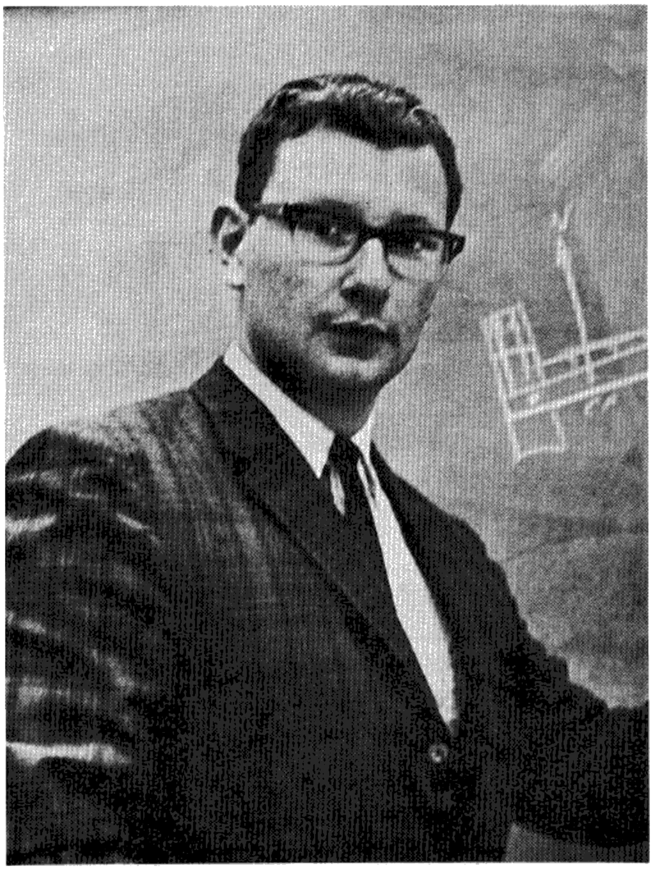
ABOUT THE AUTHOR



JIM BARROWMAN is presently employed by NASA's Goddard Space Flight Center in Greenbelt, Maryland as an Aerospace Engineer in Fluid and Flight Dynamics. Jim was born in Toledo, Ohio 25 years ago and graduated from the University of Cincinnati in 1965 with a Bachelor of Science degree in Aerospace Engineering. Jim, together with his wife Judy and their two year old daughter Julie Ann, presently reside in Hyattsville, Maryland where he continues graduate level studies at nearby Catholic University of America.

He has been employed by NASA since 1961, and worked as a co-op student trainee during the first four years. Here he performed magnetometer data reduction for the Vanguard III Satellite, was a member of a Mars Atmospheric Entry Capsule design team, assisted in the thermal design of the IMP (Interplanetary Monitoring Probe) Spacecraft, performed dynamic motion studies of the Aerobee 150A Sounding Rocket, and wrote a computer program for his aerodynamic analysis of the Tomahawk, Nike-Tomahawk, and Black Brant IIIB Sounding Rockets.

Jim's interest in Model Rocketry dates back to 1964. He enjoys working with young people, and in addition to occasional lectures to Junior and Senior High School groups on aerospace careers, he has become the senior advisor for the NARHAMS Section of the National Association of Rocketry. The method Jim developed for calculating the exact center of pressure of a model rocket earned him a First Place Senior Research and Development Award at NARAM-8 in August, 1966. He is also an active NAR Trustee and has been appointed Chairman of the NAR Publications Committee and Contest Director for NARAM-10. Jim's obviously few leisure moments are spent sailing and experimenting with his favorite model rocket - - - the boost glider.

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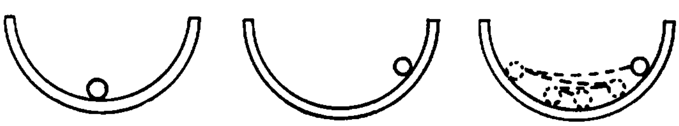
1. INTRODUCTION

As a model rocketeer, you want your rockets to have the best and safest flights possible. In order to do this, you must know before you fly them that your rockets will fly straight up and not do loops around your head. In order to fly a straight and predictable trajectory, a model rocket must be stable. The basic rule for making a stable rocket is: A rocket will be stable only if its center of pressure is behind its center of gravity. This important rule won't help you if you don't understand what the words mean and how to use them. Also, you are probably wondering why such a rule is true. The answers to these questions are found by exploring the basic scientific principles that govern how model rockets move.

2. WHAT IS STABILITY?

As stated before -- to fly a straight and predictable trajectory, a model rocket must be stable. But, exactly what is stability? To get an idea what stability means, get a small rubber ball and a round bottom bowl. When you put the ball into the upright bowl, (see Figure 1a) it will sit at the very bottom of the bowl.



1a Neutral position | 1b Displaced (disturbed) position | 1c Stable motion

Figure 1

This is called its neutral position. Now, hold the ball on the side of the bowl (see Figure 1b). In this position the ball is said to be displaced or disturbed. You can see that if you hadn't moved it, the ball would have stayed at the bottom indefinitely. Any position in which a body will remain until it is disturbed is called a neutral position. If the ball were placed on a piece of corrugated metal, it would have many neutral positions, one in each trough.

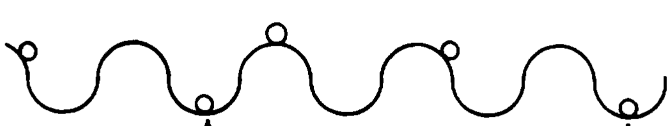
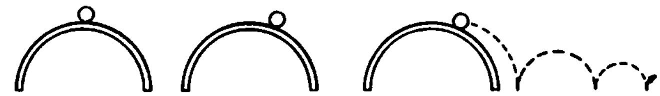


Figure 2

After displacing the ball, let it go and watch its motion. It will roll back and forth on the sides of the bowl until it stops at the bottom (see Figure 1c). It has returned to its original neutral position. The back and forth motion is called oscillation; and, because the ball returned to its neutral position, the oscillation is called positively stable or just stable. In general, any body that returns to its original neutral position after being disturbed is said to be stable.

Now turn the bowl upside-down on the table and very carefully set the ball at the top (see Figure 3a). Getting the ball to stay may be a difficult task; for if



3a Neutral position | 3b Displaced position | 3c Unstable motion

Figure 3

the ball is the slightest bit off the top (disturbed position, see Figure 3b) it will roll off the bowl and bounce away (see Figure 3c). If you succeed in getting the ball to set on top of the bowl, it will stay there in a neutral position. But, the smallest disturbance will cause the ball to again roll down and away. In general, then, any body that moves away from its original neutral position after being disturbed is said to be unstable.

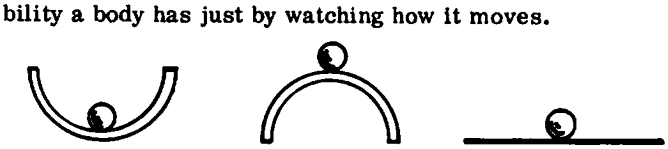
Finally, put the ball on a flat and level table (see Figure 4a). You see that it sits still no matter where on the table it was placed. That is, the ball is in a neutral position anywhere on the table. When it is

4a Neutral position | 4b Displaced position

Figure 4

displaced to another spot on the table (Figure 4b) it is again in a neutral position and does not move. It is neutrally stable. The associated general definition is: any body that is always in another neutral position after being disturbed from its original neutral position is said to be neutrally stable.

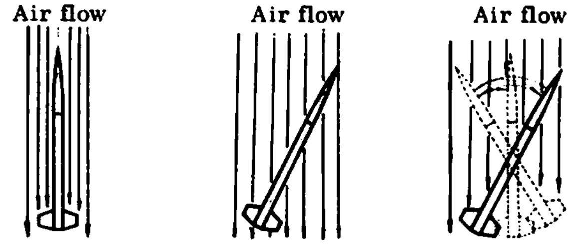
Thus, there are three types of stability; positive, negative and neutral. And, you can determine which kind of stability a body has just by watching how it moves.



Stable | Unstable | Neutral

Figure 5

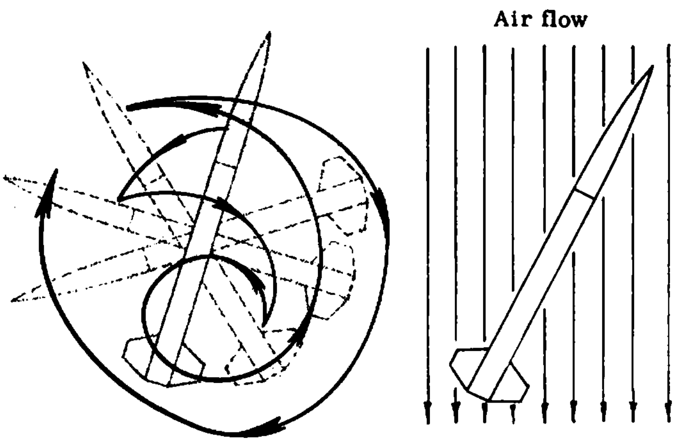
How does this apply to model rockets? Imagine a model rocket flying through still air. The air is passing smoothly over the model (see Figure 6a).



6a Neutral position | 6b Disturbed position | 6c Stable (oscillation)

Figure 6

As long as it isn't disturbed, the rocket will fly straight into the air flow. This is its neutral position. Now, if the rocket is hit, say by a wind gust from the side during flight, then it will fly at an angle to the air flow. This is its disturbed position. If the rocket then oscillates back to its neutral position (flying straight into the wind) it is stable. But, if it starts to fly at wider and wider angles to the air flow and eventually flips end-over-end in the air, it is unstable.



7a
Unstable
(flip-flops)

7b
Neutrally stable
(no motion)

Figure 7

If the rocket is neutrally stable, it will continue to fly at an angle to the air flow, no matter what the angle is.

Of course, what is shown in Figures 6 and 7 is what you would see if you were flying along with the rocket.

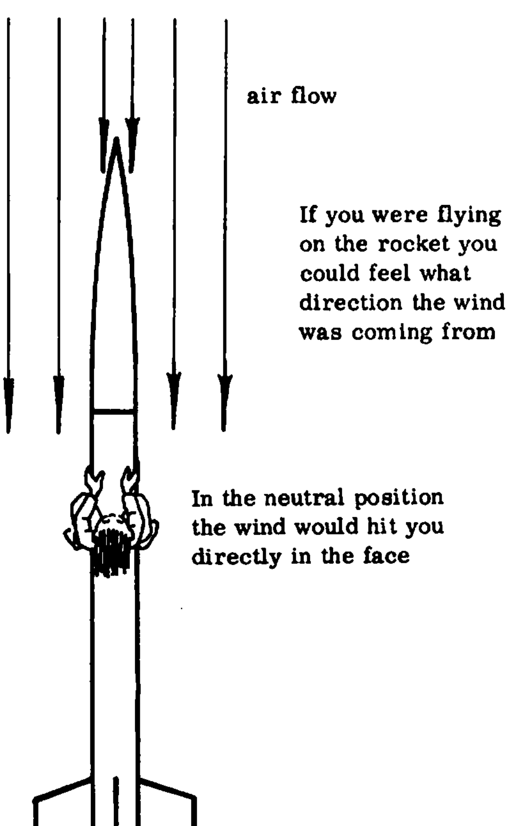


Figure 8

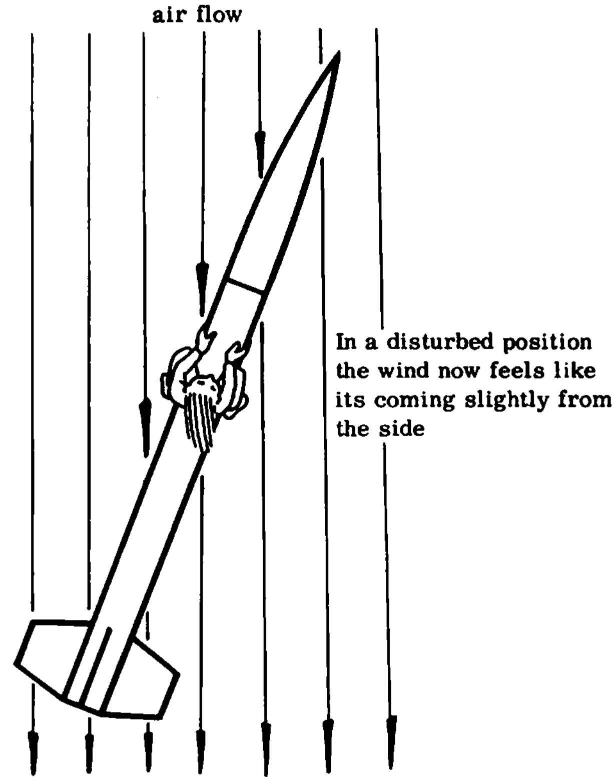
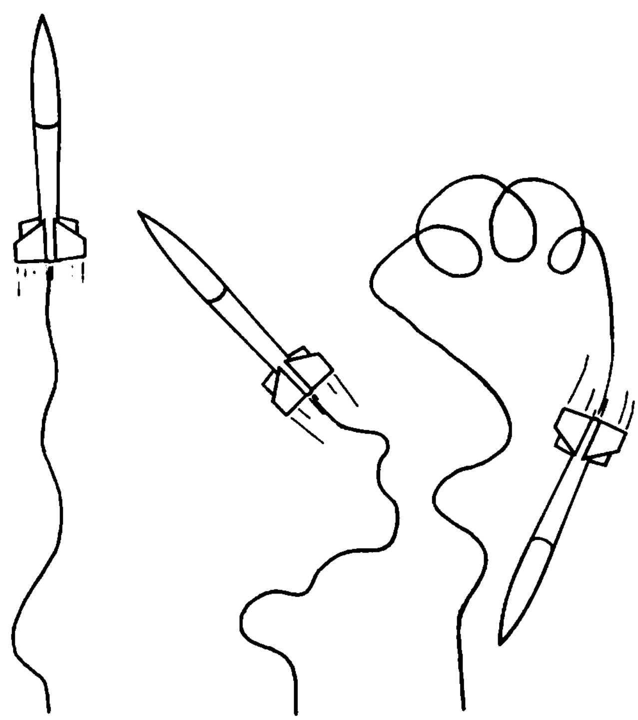


Figure 9

What you would really see while watching from the ground is shown in Figure 10.



10a
Stable
(oscillation)

10b
Neutrally
stable

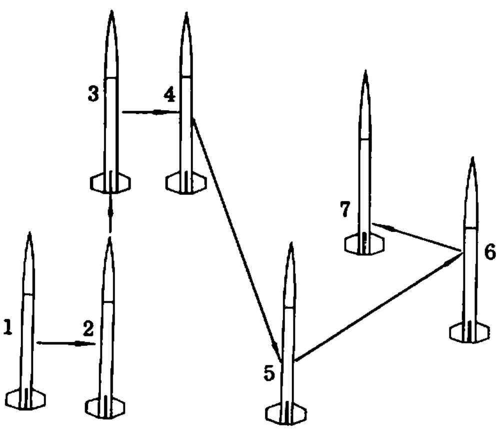
10c
Unstable
(flip-flops)

Figure 10

Stability in general, then, is a description of how a body (in this case a rocket) will behave while it is in motion. Simply by stating that a rocket is stable or unstable, you can describe a very complex pattern of motion.

3. ROCKET MOTIONS AND FORCES IN FLIGHT

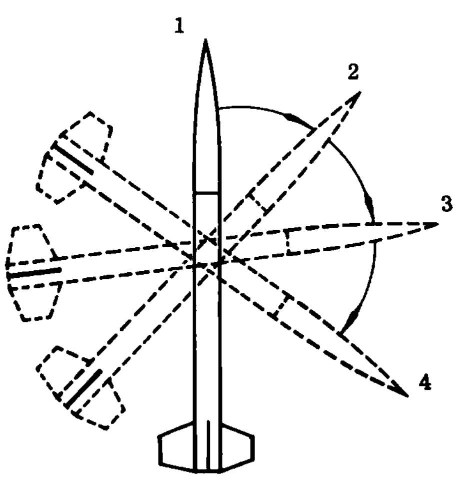
The motion of any body can mentally be separated into two different kinds of motion, translational and rotational. Figure 11 shows some examples of the translational motion of a rocket.



Translational motion

Figure 11

Notice that the rocket moves sideways, up, down, and across to different places but it always points in the same direction. The rotational motion of a rocket is shown in Figure 12. In this case, the rocket points in different directions while it stays in the same place.



Rotational motion

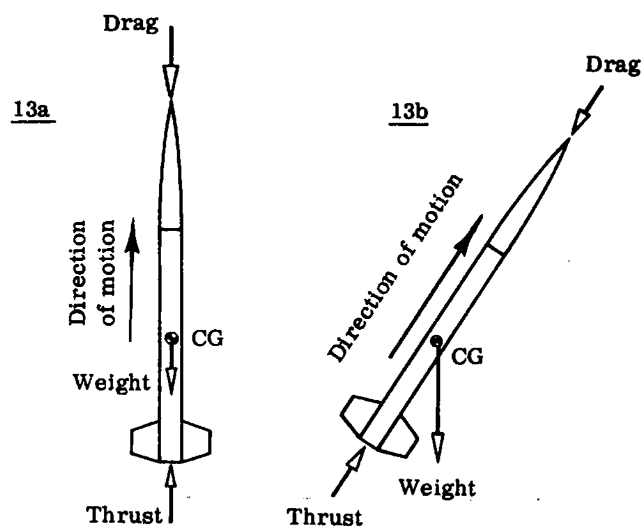
Figure 12

Rotation of any body is always about a straight line or axis. For example, a wheel rotates on an axle or a propeller rotates on a shaft.

When you ask how high a rocket goes or how far away it lands, you are interested in the rocket's translational motion. On the other hand, when you talk about a rocket's stability, you are concerned with its rotational motion. The real motion of a rocket, of course, is a simultaneous combination of its translational and rotational motions.

Any motion of a body is caused by the forces acting on it. The forces acting on a model rocket are its weight, the rocket engine's thrust; and the air pressure forces caused by the air flowing over the rocket. Just as the motions of the rocket can be mentally divided into two kinds, even though they occur simultaneously, so can the forces acting on it. They can be broken up so that there is a set of forces associated with the translation of the rocket and a separate set associated with its rotation.

The forces associated with translation are the rocket's weight; the engine's thrust; and the resistance of the air to the rocket's motion, called the aerodynamic drag. These forces are shown schematically in Figure 13. Notice that thrust is along the length of the rocket, drag is opposite the direction of motion, and weight always points down toward the ground.



Translational forces in vertical flight

Translational forces in slanted flight

Figure 13

Note also that the translational forces all act through the Center of Gravity (C.G.) of the rocket.

The forces associated with the rotational motion of the rocket are all those forces that do not act through the rocket's center of gravity. These forces are essentially the air pressure forces that act perpendicular to the rocket's centerline such as the lift on the fins and the nose. All these forces can be added together, and the total air pressure force acting perpendicular to the centerline can be considered to act at the center of pressure (C.P.). In Figure 14, this total force is represented by the letter N. The C.P. and C.G. locations are shown as they would be on a stable rocket using the standard symbols, ⊕ for C.G., and ⊙ for C.P.

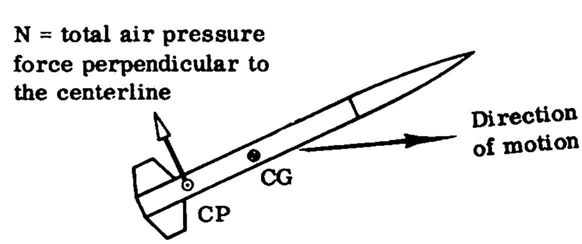


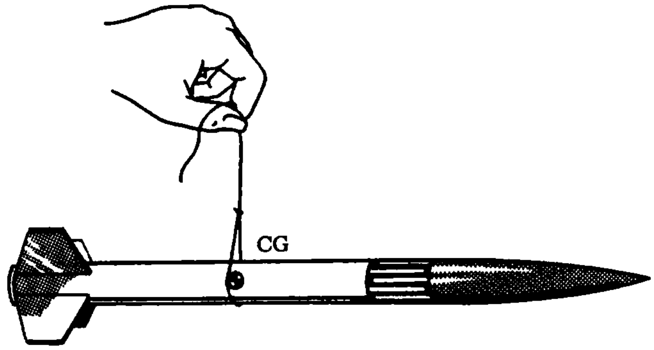
Figure 14

Notice that the rocket is flying in one direction while it is pointed in a different direction. It is in a disturbed position. The rotational forces on a rocket act only when it is in a disturbed position. The difficult thing about the rotational forces acting on a rocket is that while the forces affect the rotational motion of the rocket, the rotational motion, in turn, affects the forces and the C. P. location.

The division of a rocket's motion into two different types of motion leads directly to the separate consideration of the center of gravity (C.G.) and the center of pressure (C.P.). Each of these quantities is discussed in Sections 4 and 5. Their interrelation and its effect on model rocket stability are considered in Section 6.

4. THE CENTER OF GRAVITY

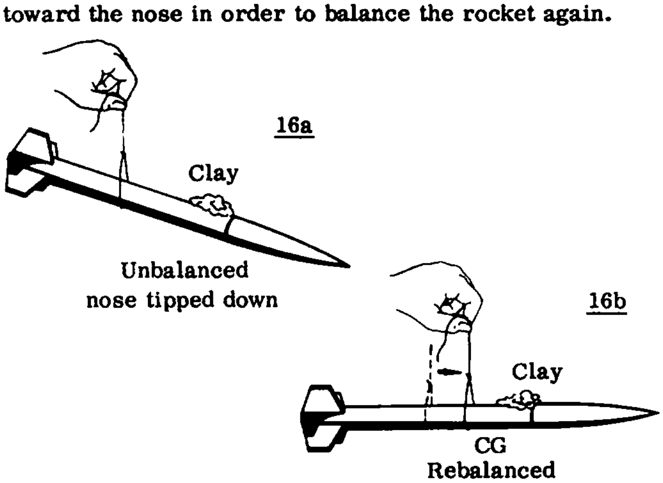
The center of gravity (C.G.) of a rocket is the point at which all the weight of the rocket seems to be concentrated. That is, there is as much weight distributed ahead of the rocket's C.G. as there is distributed behind it. Another name for the C.G. is the rocket's balance point. If you tie a string to the rocket at the C.G., the rocket will remain level, or balance.

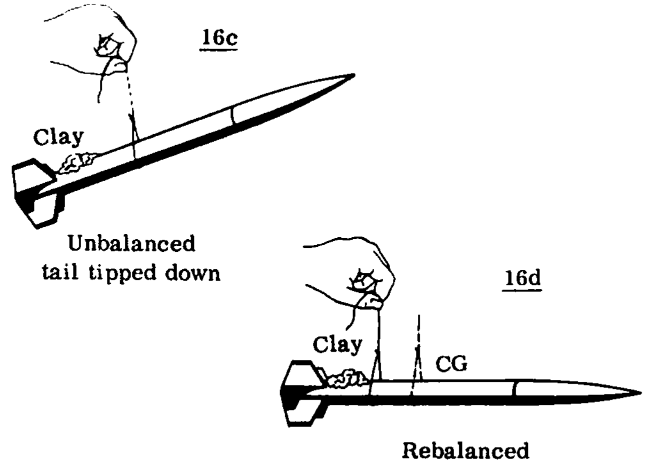


Balanced rocket

Figure 15

The force you feel on the string when you balance the rocket is the rocket's weight. This total weight is actually the sum of all the weights of the different pieces of material that make up the rocket. If you add more material to the rocket (like a lump of clay) it will weigh more. Also, if the additional material is attached, say to the nose, the nose will tip down and you will have to move the string toward the nose in order to balance the rocket again.



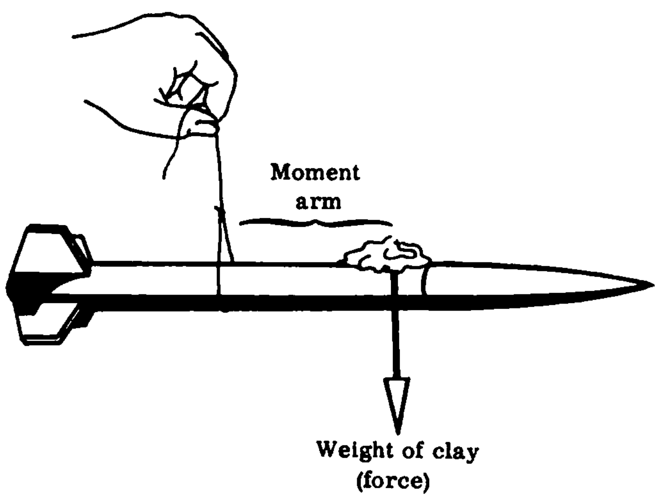


Addition of material

Figure 16

It is apparent that the weight of the material does more than add weight to the rocket. It also tends to rotate the rocket so that the end on which the material was added will tip down.

The tendency of any force, such as the weight of the clay, to rotate a body is called a moment. The size of a moment depends on the force itself as well as the distance between the force and the axis about which the body is rotating. The distance involved is called the moment arm. In this case, the force involved is the weight of the clay while the moment arm is the distance between the clay and the point where the string is tied.

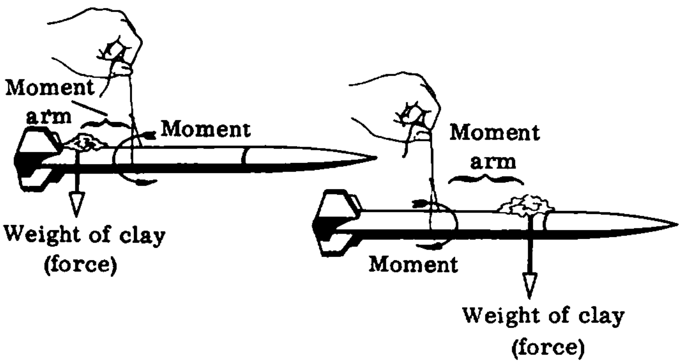


Force and moment arm

Figure 17

If you move the clay farther and farther from the string, the moment arm is increased and the rocket will tip more and more. Also, adding more clay to the same spot on the rocket increases the weight force and causes the rocket to tip more. In general, a moment is increased by either increasing the force or by increasing the moment arm. Mathematically, the size of a moment is the product of the force and the moment arm.

Moment = (Force) X (Moment Arm)



18a Moments 18b

Figure 18

The curved arrow shown in both figures above is the standard symbol for a moment. Notice that they point in opposite directions in the two different pictures. You can see, then, that a moment not only has a size (force x moment arm), it also has a particular direction. The direction of a moment is the direction that it tends to rotate the body on which it acts.

Remember -- a moment is always about a specific line or axis. If you move the axis, you will change the moment arm and, therefore, the moment itself. When the string around the rocket is moved toward the clay, the rocket becomes level again. The moment caused by the clay weight has been reduced by reducing its moment arm. At the same time, a new moment acting in the opposite direction has been introduced. This new moment is simply the original rocket weight times its distance to the new balance point as shown below.

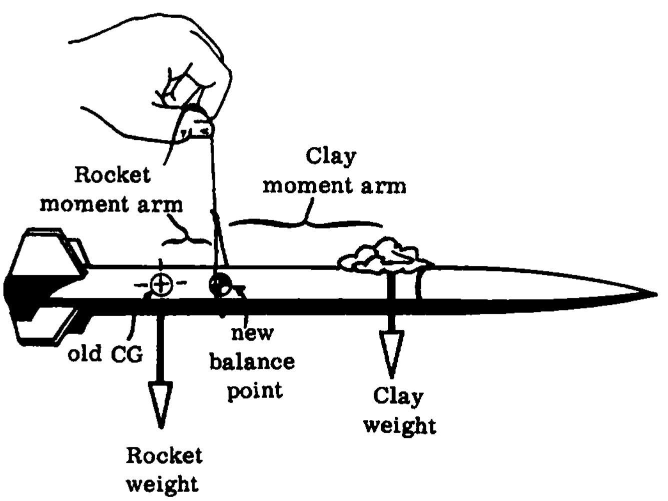


Figure 19

The new balance point is where the two moments are equal in size but acting in opposite directions.

$$\left(\text{Rocket Weight}\right) \times \left(\text{Rocket Moment Arm}\right) = \left(\text{Clay Weight}\right) \times \left(\text{Clay Moment Arm}\right)$$

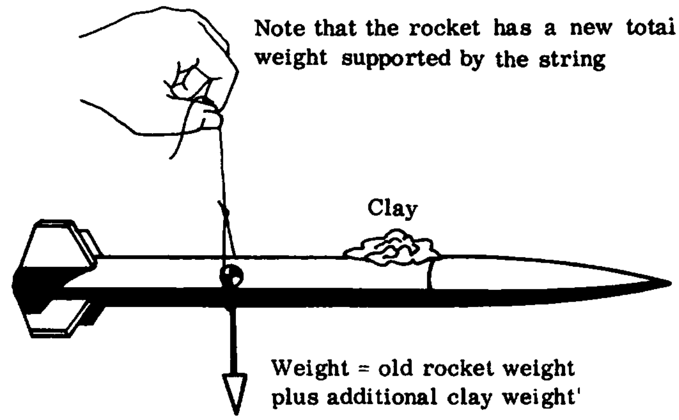


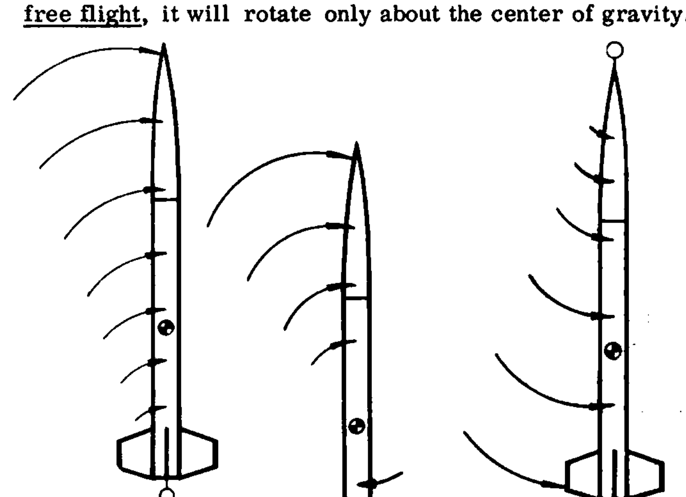
Figure 20

The new string position is the center of gravity of the rocket with clay attached to it (see Figure 16).

If a lump of clay added to the rocket has a moment associated with it, then each of the different pieces of material that make up the rocket must have a moment associated with it. At the beginning of this Section, it was stated that there is as much weight distributed ahead of the rocket's C.G. as there is distributed behind it. In terms of moments, this means the moment due to the weight of the material ahead of the C.G. equals the moment due to the weight of the material behind it. Thus, the rocket will remain level when you hang it by the C.G.

It is important for you to realize that the position of the center of gravity on a rocket (or any body) is associated with the distribution of the weight and not the weight itself. This same idea will be used in explaining the center of pressure.

The center of gravity is important to stability not because the rocket balances there; but because when a rocket is in free flight, it will rotate only about the center of gravity.



21a Rotation about the tail is not possible in free flight

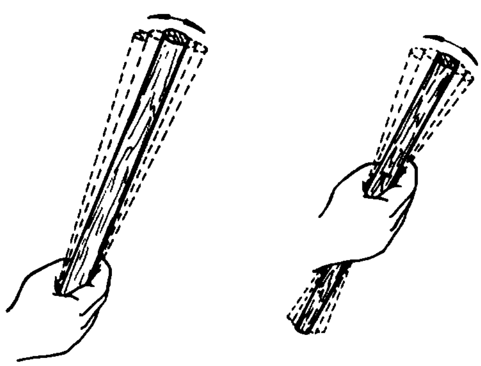
21b Only possible rotation in free flight is about the CG

21c Rotation about the nose is not possible in free flight

Rotation about the center of gravity

Figure 21

Any body that is free to rotate in any way will naturally rotate about an axis through its center of gravity. You can force a body to rotate about a different axis by holding it, but then the body is no longer free to rotate naturally. A body will rotate about its C.G. simply because it is easier for it to rotate there than it is for it to rotate anywhere else. That is, it takes the least amount of effort to rotate a body about its center of gravity.* To see this for yourself, grip a long heavy stick at one end and swing it back and forth in front of you using only your wrist. Then grip it at its center of gravity and again swing it back and forth. You will find that it is noticeably easier to swing the stick about its C.G.



22a 22b

Figure 22

In review, there are two major facts that must be kept in mind about the C.G. when you are interested in model rocket stability. First, the position of the center of gravity of a rocket is determined by the distribution of the weight of the rocket. Second, when a rocket is flying free it will rotate only about its center of gravity.

5. THE CENTER OF PRESSURE

The center of pressure (C.P.) is similar to the center of gravity except that the forces involved are the air pressure forces acting on the rocket when it is flying. The C.P. can be defined in identically the same manner as the C.G. The center of pressure of a rocket is the point at which all the air pressure forces on the rocket seem to be concentrated. That is, there is as much air pressure force distributed ahead of the center of pressure as there is distributed behind it. In terms of moments, there is as much moment due to the air pressure force ahead of the center of pressure as there is behind it.

*As a matter of fact, everything that happens in the universe happens in such a way that the least amount of effort is required. This was mathematically proven by Sir W. R. Hamilton in the late Nineteenth Century. This basic physical principle is called Hamilton's Principle of Least Action. If you study advanced mechanics or physics in college you will learn about Hamilton's Principle and how it can be proven.

In the figure below, the size of the air pressure forces that are distributed over the length of the rocket and on the fins are represented by the length of the arrows along the top of the rocket.

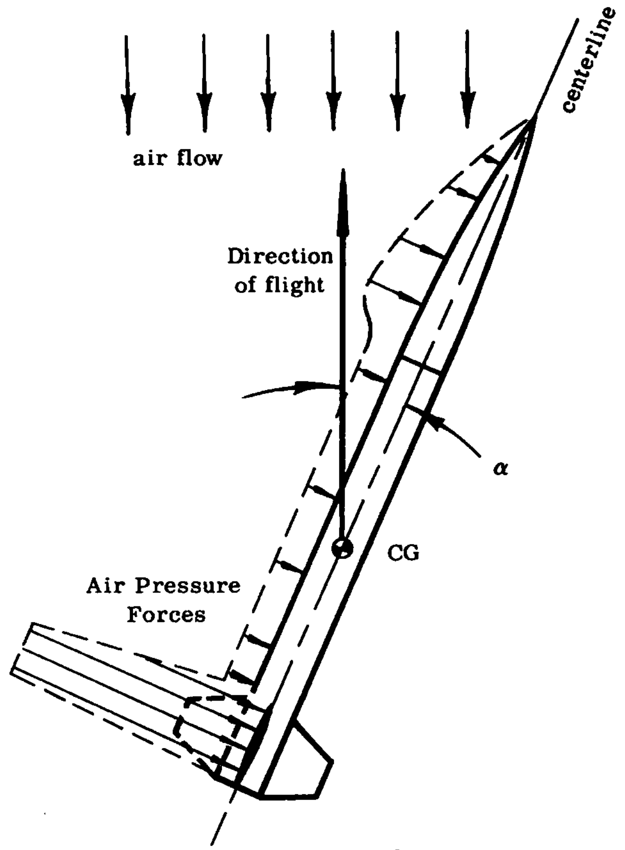


Figure 23

As you can see, the rocket is in a disturbed position (exaggerated in the drawing). That is, it is at a slight angle to the direction it is flying. As a result, it is at an angle to the direction of the air flow over it. This is called the angle-of-attack and is represented by the Greek letter Alpha, α. Notice that the air pressure forces pictured above are all perpendicular to the rocket centerline. These are called the normal (mathematical term meaning perpendicular) forces acting on the rocket. Simultaneously, there are also axial air pressure forces on the rocket. Although the axial forces are important in calculating the altitude performance of the rocket, they do not influence its center of pressure.

The distribution of normal forces shown above represents how the forces actually act on a typical model rocket flying at an angle-of-attack. However, as was mentioned in Section 3 on rocket motions and forces, these distributed normal forces can be added together and their combined effect on the model can be reproduced by a total normal force called N. Just as the total weight acts at the C.G., the total normal force acts at the center of pressure or C.P.

Figure 24 is equivalent to Figure 23 except that the distributed normal forces have been replaced by N acting at the C.P.

Just as the center of gravity location depends on the rocket's weight distribution, the location of the center of pressure depends strongly on the way the air pressure forces are distributed over the rocket.

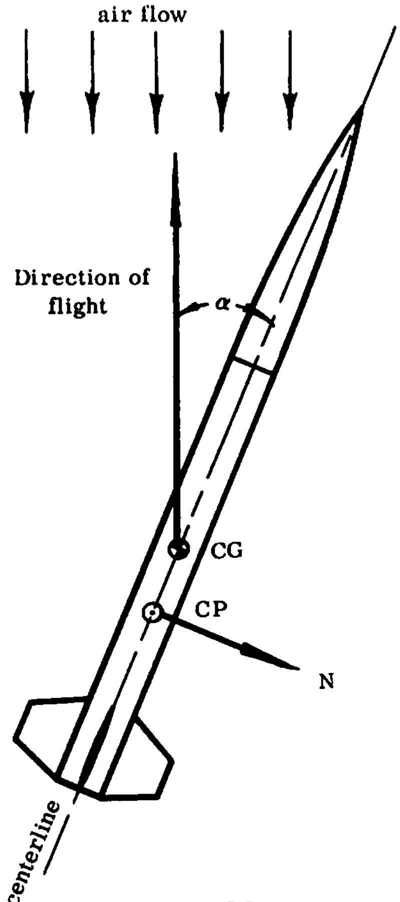
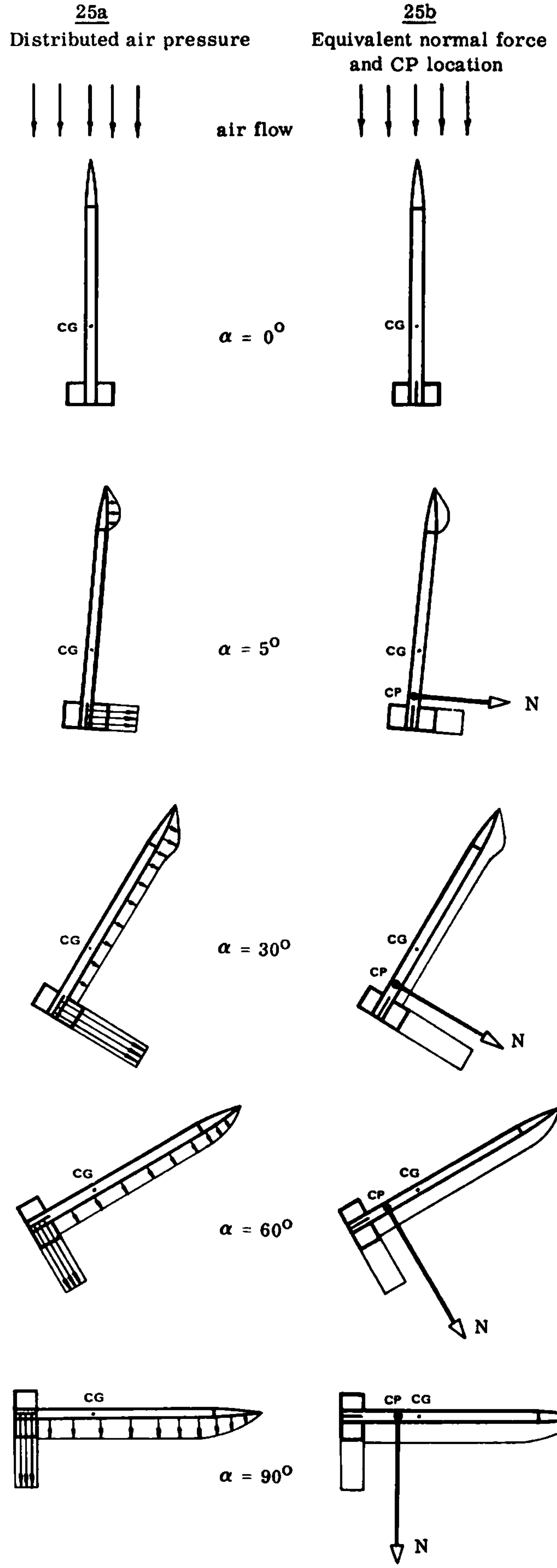


Figure 24

The angle-of-attack at which a rocket flies has a strong effect on the size and shape of the normal force distribution on a rocket. The left hand side of Figure 25 shows how the normal force distribution on a typical model rocket looks when it is flying at different angles-of-attack. The right hand side shows the equivalent normal force and C.P. location for each α . The equivalent total normal force gets larger as the angle-of-attack increases. But, more important, the distribution of the normal forces changes a great deal as the angle-of-attack increases. As the distribution changes, the center of pressure moves. As shown on the right hand side of Figure 25, the location of the center of pressure moves forward as the angle-of-attack increases.

In terms of moments, the increase in angle-of-attack causes the normal forces to build up all along the rocket. However, the moments of the normal forces near the nose increase faster than the moments of the normal forces near the tail. This means that there is no longer as much moment due to air pressure force behind the C.P. as there is ahead of it. Just as the C.G. has to move toward any added weight in order to decrease its moment arm and rebalance the rocket; the C.P. moves toward the nose so that the moments ahead of C.P. and behind it will again be the same.

The fact that the C.P. moves forward as the angle-of-attack increases is very important since it can affect a rocket's stability.

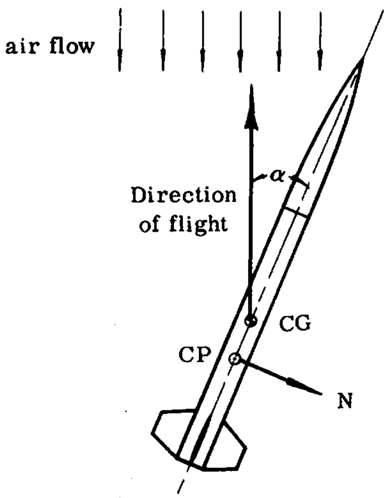


Variation of CP location with angle-of-attack
Figure 25

6. ELEMENTS OF MODEL ROCKET STABILITY

Remember from Section 4 that a rocket in free flight will rotate only about its center of gravity. Remember, also, that the only thing that can cause a rocket to rotate is a moment. The two things that determine a moment are a force and a moment arm.

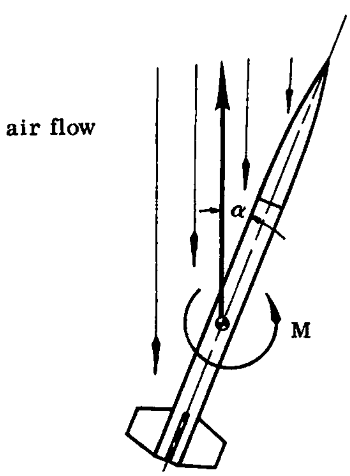
As shown in Section 5, a rocket flying at an angle-of-attack (disturbed position) has its total normal air pressure force acting at its center of pressure.



Normal force and CP
(stable condition)

Figure 26

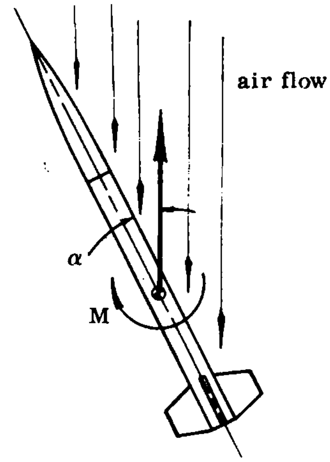
The normal force, N, and the distance between the center of pressure and the center of gravity (moment arm) combine to form a moment, M, about the center of gravity.



Aerodynamic moment
(stable condition)

Figure 27

Since the distance between the C.G. and C.P. is the moment arm associated with the normal air pressure force it is quite important and has been given the special name static margin. Since the moment, M, is associated with the air pressure forces, it is called aerodynamic moment. The aerodynamic moment tends to rotate the rocket about the center of gravity. In the figure shown above, the rocket will rotate back toward the direction of motion decreasing the angle-of-attack. Since the rocket is rotating as it reaches zero angle-of-attack, it will swing past its direction of motion and will again be at an angle-of-attack.



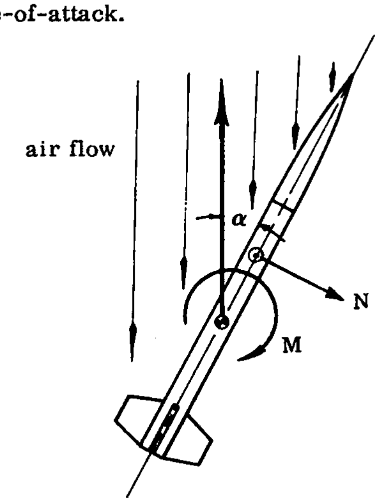
Stable oscillation

Figure 28

But, the normal force and resulting aerodynamic moment at the new α tend to again rotate the rocket toward the direction of motion. This process is repeated as the rocket swings back and forth less and less until it finally stops swinging and flys pointing in the direction of motion (zero angle-of-attack).

By now you may have recognized that a rocket at zero angle-of-attack is in its neutral position and that the process described above is a stable oscillation such as the one described in Section 2. Notice in the figures shown above that the rocket's C.P. is behind its C.G. This is exactly the requirement for stability that was stated at the beginning of this report -- A rocket will be stable only if its center of pressure is behind its center of gravity.

But, what will happen when the C.P. is ahead of the C.G.? The figure below shows this situation on a rocket that is at an angle-of-attack.

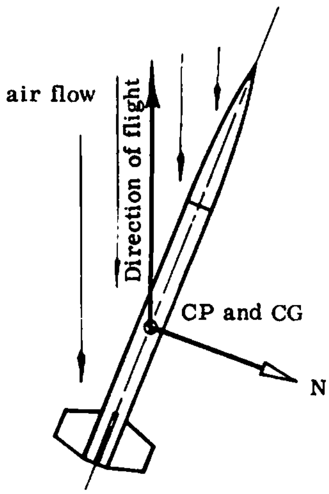


Aerodynamic Moment
(unstable condition)

Figure 29

In this case, the aerodynamic moment tends to rotate the rocket away from its direction of motion (neutral position). From the associated definition in Section 1, it is obvious that a rocket that has its C.P. ahead of its C.G. is unstable and will flip-flop all over the sky.

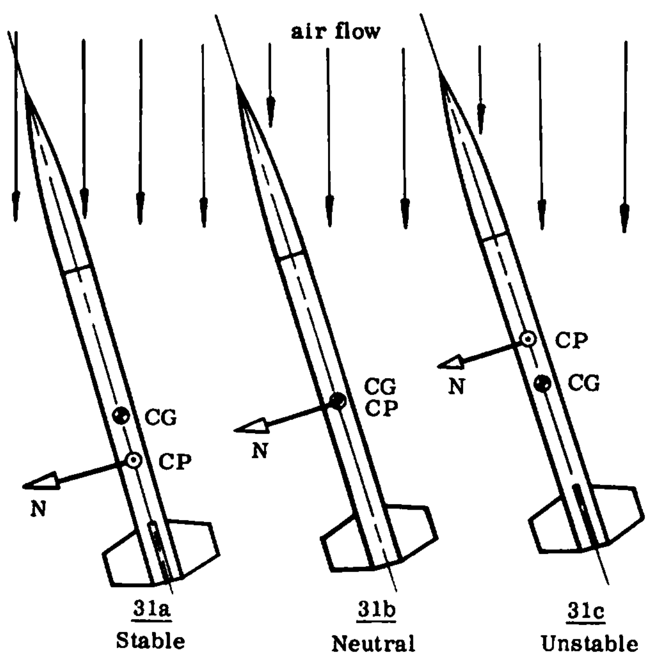
Having looked back at Section 1, you may wonder what C.P.-C.G. relationship corresponds to neutral stability. To be neutrally stable, a rocket must remain at any angle-of-attack at which it is flying. In order to remain at any given angle-of-attack a rocket must have no tendency to rotate. Thus, there can be no moment associated with the normal air pressure force acting on the rocket. For this to be true, the static margin must be zero; or, the C.P. must be at the same location as the C.G.



Neutral stability (M = 0)

Figure 30

In review, the three types of model rocket stability and the associated C.P.-C.G. relationships are shown below. Using arrows to represent the normal force obviously helps in visualizing the rotation about the C.G.



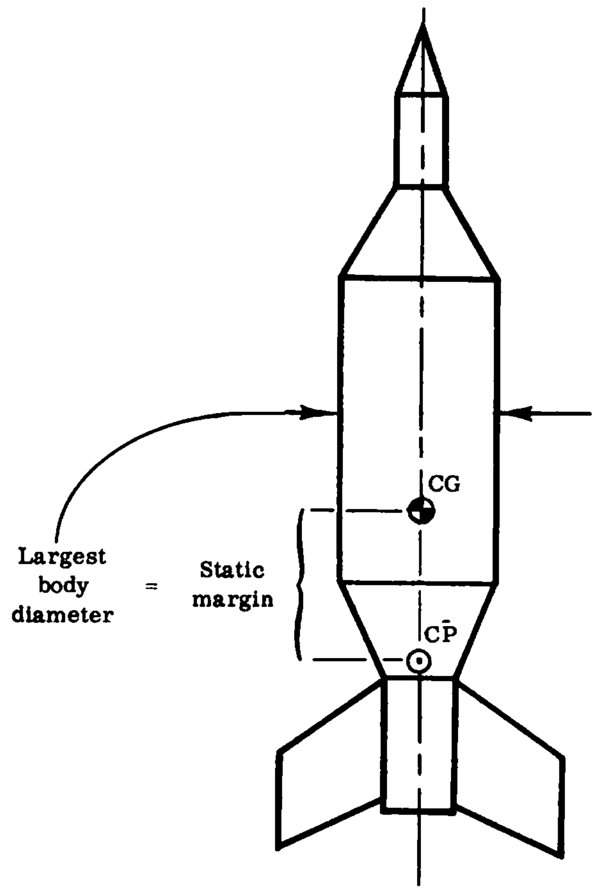
Types of stability

Figure 31

Knowing that your rocket is stable is not enough. You must also know how much stability it has. That is, how quickly does the rocket oscillate back to its neutral position after it has been disturbed. Since it is the moment arm for the aerodynamic moment, the static margin has the greatest effect on a rocket's stability. Thus, for a stable rocket, the larger its static margin, the more stable it will be.

The importance of the effect of angle-of-attack on the position of the C.P. now becomes apparent. As a rocket's angle-of-attack increases, the C.P. moves forward, the static margin decreases, and the rocket becomes less stable. It's possible that the C.P. might even move forward of the C.G. causing the rocket to become unstable. Obviously, you want your rockets to have a static margin that is large enough to insure that it will be stable and fly at small angles-of-attack.

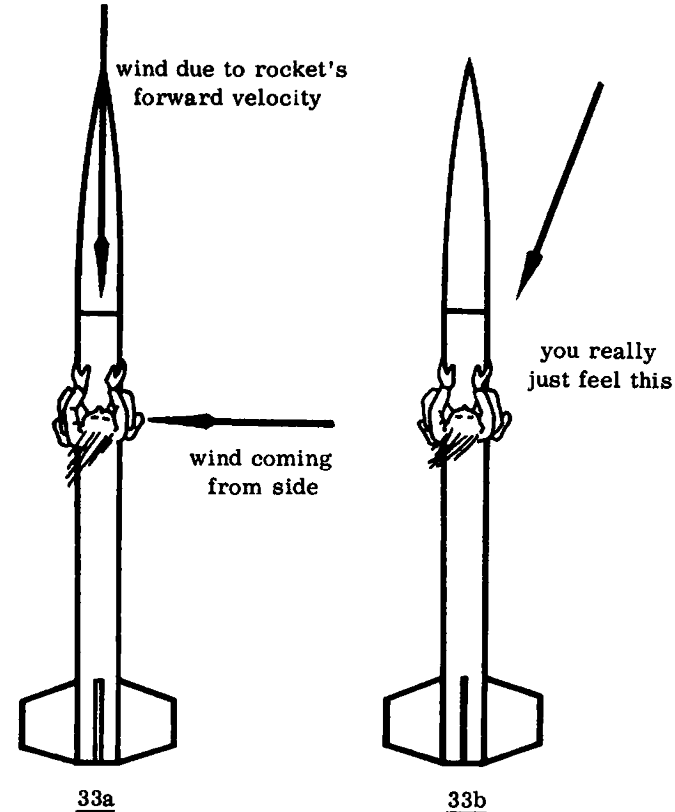
But, if your rocket is too stable, it will weathercock too easily. A good rule of thumb is to have the static margin equal to the largest diameter of the rocket.



Ideal static margin

Figure 32

The reason a rocket weathercocks or consistently arcs over on a windy day is that the rocket is at an angle-of-attack to the wind even as it leaves the launch rod. If you were riding along with the rocket it would seem as if the wind was off at an angle to your face even though you know you were leaving the rod going exactly straight up.



Weathercocking

Figure 33

The wind is not just from the side as you felt it just prior to lift-off. The total wind is now the wind due to the rocket's velocity forward plus that of the side wind. The effect of the side wind on this angle is more pronounced if you were riding a heavier rocket which leaves the rod at a much slower velocity.

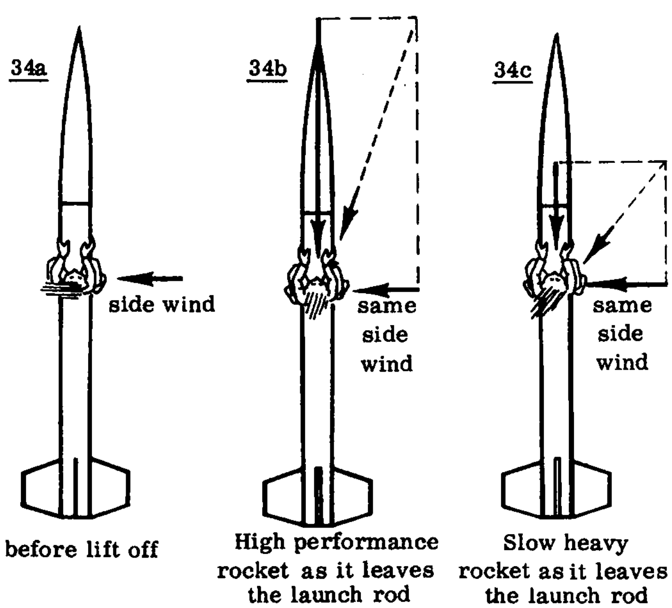


Figure 34

Now that the rocket's motion is not restrained to straight up any more by the launch rod it can rotate freely about its natural free flight pivot point, which is the C.G. Since the wind is hitting the rocket at an angle, a normal force is produced. If the rocket is stable (C.P. behind C.G.), the resulting moment tends to rotate the rocket directly head on into the wind, thereby gradually reducing the angle-of-attack of the wind to zero.

Obviously, the larger the moment due to the normal force acting at a distance from the C.G., the quicker the rocket responds and rotates all the way to zero angle.

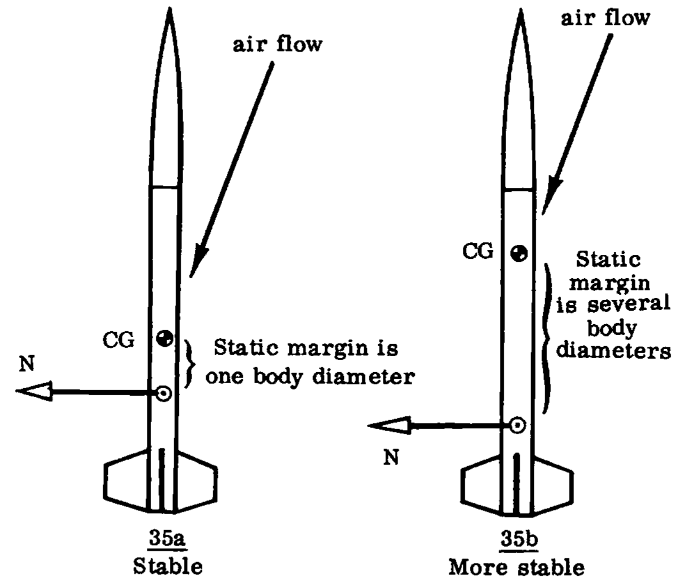


Figure 35

The above illustration shows that the moment about the C.G. will indeed be larger for the more stable rocket, because even though the forces are identical, the moment arms are different.

One second after leaving the rod the more stable rocket may already be aligned to zero angle-of-attack while the rocket with a static margin of stability of only one body diameter may still be completing its correction because of its smaller restoring moment.

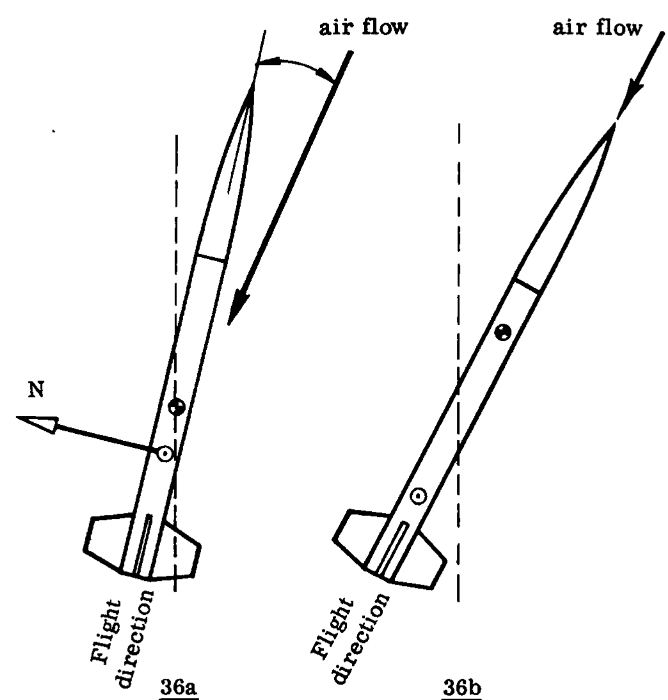


Figure 36

from the ground we would see

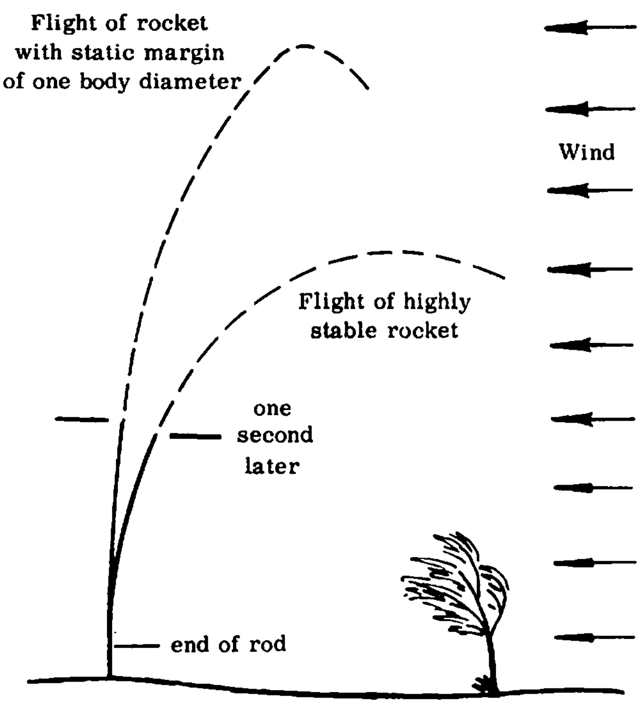


Figure 37

Once the causes for weathercocking are understood, we can immediately see ways to reduce the effect:

a) Use a longer than usual launch rod so that the rocket has more time to build up forward speed. The larger the speed, the less the angle for a given crosswind.

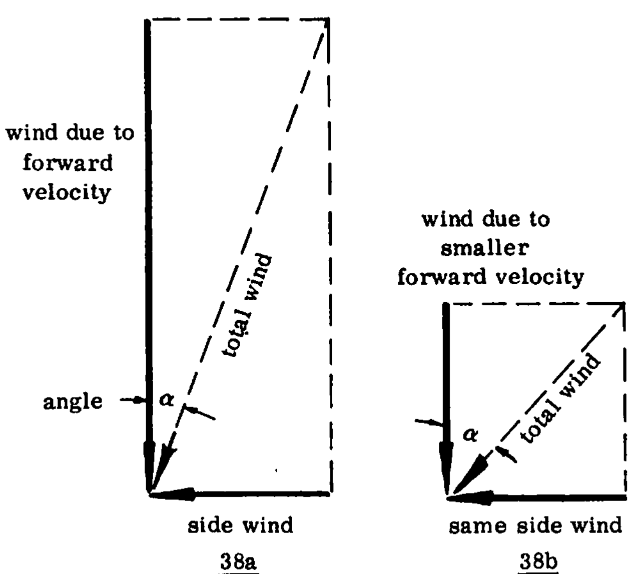


Figure 38

b) Use rockets with static margins not much greater than one largest body diameter. More stability will mean more weathercocking tendency.

c) Use the highest average thrust motor possible so that the velocity when the rocket leaves the restraint of the rod is as large as possible.

7. DETERMINING STABILITY

There are a number of dependable methods that you can use to determine the stability of your rockets before you fly them. They range from purely experimental to purely theoretical.

SWING TEST

The best experimental method is to swing the fully prepared rocket (parachute and engine inserted) on a string attached to the rocket at its center of gravity. First, balance test the rocket to find its C.G. Then secure the string firmly at the C.G. with a piece of tape or straight pin. Check to see if the area is clear so you won't hit anyone or smash the rocket when you swing it. Be careful to start the rocket so that it is pointing in the direction that it is moving. Remember that if it has a large angle-of-attack, it may be unstable at that angle even though it is actually stable at smaller angles-of-attack. If the rocket tends to stay pointed in the direction it is moving as you swing it, then it is stable. Several tries may be necessary before you can start the rocket swinging smoothly; but if the rocket simply will not stay pointed in the direction it is moving, then it probably doesn't have adequate stability.

LOCATING THE CENTER OF GRAVITY

Without actually swing-testing the rocket, you can separately determine the rocket's center of gravity and center of pressure. Then if the C.P. is properly behind the C.G. the rocket will be stable. The C.G. location can be found by balance testing it, as shown in Figure 15. However, if you are designing a rocket and don't have it completely built, then a theoretical technique must be used. Such a technique for determining a rocket's C.G. location is given in Centuri's Technical Report TIR-33.

CARDBOARD CUT-OUT METHOD FOR LOCATING THE CENTER OF PRESSURE

There are two major methods available for determining the location of your rocket's center of pressure location. The best technique for beginners is to find the rocket's Center of Lateral Area (C.L.A.). This is the position the C.P. would have if the rocket were flying at an unrealistic angle-of-attack of 90°. Thus, it is the forward most position that the C.P. can have. To find the C.L.A. of a rocket, draw an outline of the rocket including the fins on a sheet of stiff cardboard. Cut the outline out and balance it on a ruler or with a pin as shown below:

39a

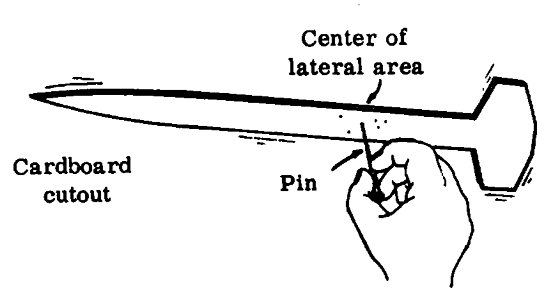


Figure 39

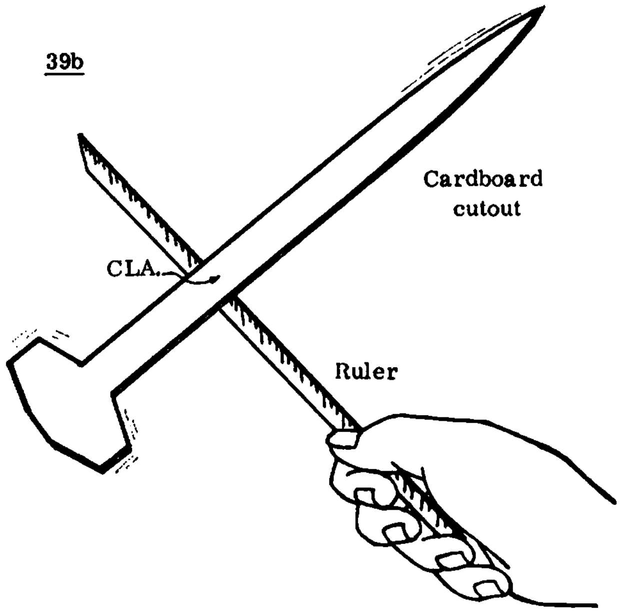


Figure 39

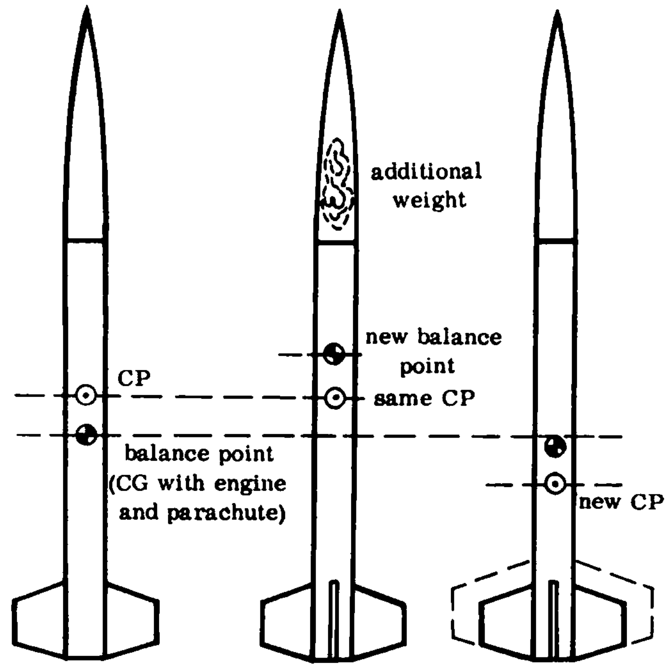
The point where the cutout balances is the rocket's C. L. A. If the cardboard is not stiff enough it will just sag and won't give the proper balance point. If the C. L. A. location of the rocket is behind its C.G. location, then the rocket will definitely be stable. A static margin of one half ($\frac{1}{2}$) the rocket's largest body diameter is quite adequate when you are using the C. L. A. cutout method.

Of course, a stable model rocket will never fly at an angle-of-attack of 90°. Actually, the static margin of a stable rocket will be larger than indicated by the center of lateral area location. Thus, if you use the C. L. A. cutout method, your rockets will tend to be overly stable and weathercock very easily. To prevent this, you can theoretically calculate your rocket's true C. P. location when it is flying at angles-of-attack near zero. A method for accurately determining a model rocket's true C. P. location is given in Centuri's TIR #33.

When working with the true C. P. location you must always be careful to provide an adequate static margin. Remember that one maximum body diameter is the smallest safe static margin.

8. OPTIMIZING STABILITY

Every rocketeer is concerned with the question of how high will his rocket go. The more sophisticated modeler realizes that stability requirements can and will affect altitude performance. If a rocket checks out as unstable, one has two alternatives to correct this. The first is to add weight to the nose to bring the C.G. adequately ahead of the C. P. As you know, though, the heavier a rocket is the lower the altitude it can attain. The second alternative is to increase the fin area in an attempt to shift the C. P. safely aft of the C. G. While this technique adds less overall weight to the rocket it adds aerodynamic drag thereby also reducing potential altitude. Besides, it has the disadvantage of requiring reconstruction in the case of a completed model.



40a
Unstable configuration

40b
Add weight
to nose

40c
Increase fin area
(note that CG shifts
slightly to the rear)

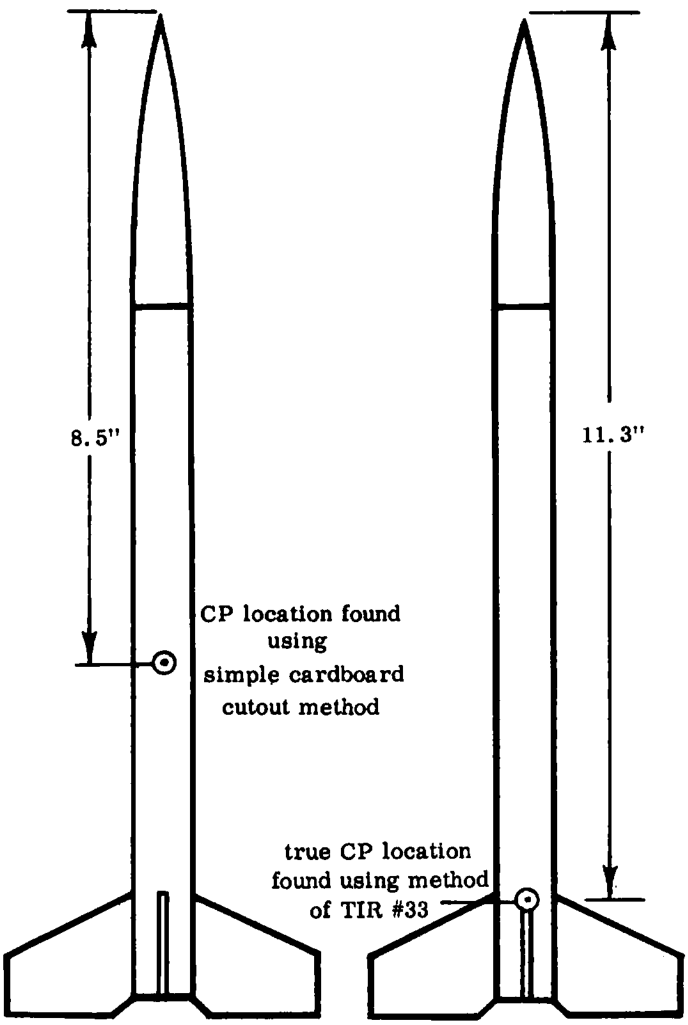
Techniques for making an unstable rocket stable

Figure 40

Using the criteria that the static margin (or distance the C.G. lies ahead of the C. P.) must be at least one maximum body diameter, it is easy to see that the C. P. location strictly dictates the C.G. location. A rocket with a larger static margin is obviously carrying more weight and/or has more fin area than is absolutely necessary. Don't forget that the weathercocking tendency and consequent reduction in peak altitude is also more prevalent for the excessively stable rocket.

If you are interested in comparing the exact effects that weight savings and aerodynamic drag improvements have on peak height, it is recommended that you obtain Centuri's TIR #100 which contains altitude performance graphs. No mathematics at all is required to find heights using these graphs, but the answers are restricted to idealized perfectly straight-up flights.

The competition oriented rocketeer should be especially aware of the influence of the method used in determining the center of pressure (C. P.) location. The simple cardboard cutout method gives a C. P. location for a rocket flying sideways, which may be one half to as much as four maximum body diameters ahead of the C. P. found using the method that gives the true C. P. for a rocket flying at zero angle-of-attack.



CP locations for Centuri's four-finned JAVELIN

Figure 41

Admittedly, there is more effort involved in finding the C. P. using TIR #33, but from the above illustration it can be seen that the choice of method used to find C. P. results in a considerable difference for the definition of a safe C.G. location. In order to check out as stable, a rocket whose C. P. has been found using the somewhat crude cardboard cutout method will require a more forward C.G. location than if the C. P. was found for the aligned flight condition. Keeping in mind that the true C. P. is the only one of real concern we can be quite sure that the rocket whose static margin is based on the true C. P. will be the better performer, as less weight penalty exists.

It should be mentioned at this time that if the C.G. was naturally ahead of the true C.P. by more than one body diameter to start with, we would not improve performance by adding weight to the tail to shift the C.G. closer to the optimum flight performance location. The rocket would be fine to fly as is, but in the interest of better performance one could consider removing weight near the nose (perhaps hollowing the nose cone itself) and removing fin area to improve aerodynamic efficiency.

At present, no one has established a simple fudge factor to convert the C. P. found using the cardboard cutout method to the true C. P. location. The difference between the two methods, using the number of maximum body diameters as a measurement, varies with each and every rocket. Safety conscious model rocketeers should not guess at the true C. P. location, especially when the tool for actually finding it is available. As previously stated, you can safely use a static margin of <u>one half</u> of a maximum body diameter with the cardboard cutout method, while the true C. P. requires <u>one</u> maximum body diameter for its static margin.

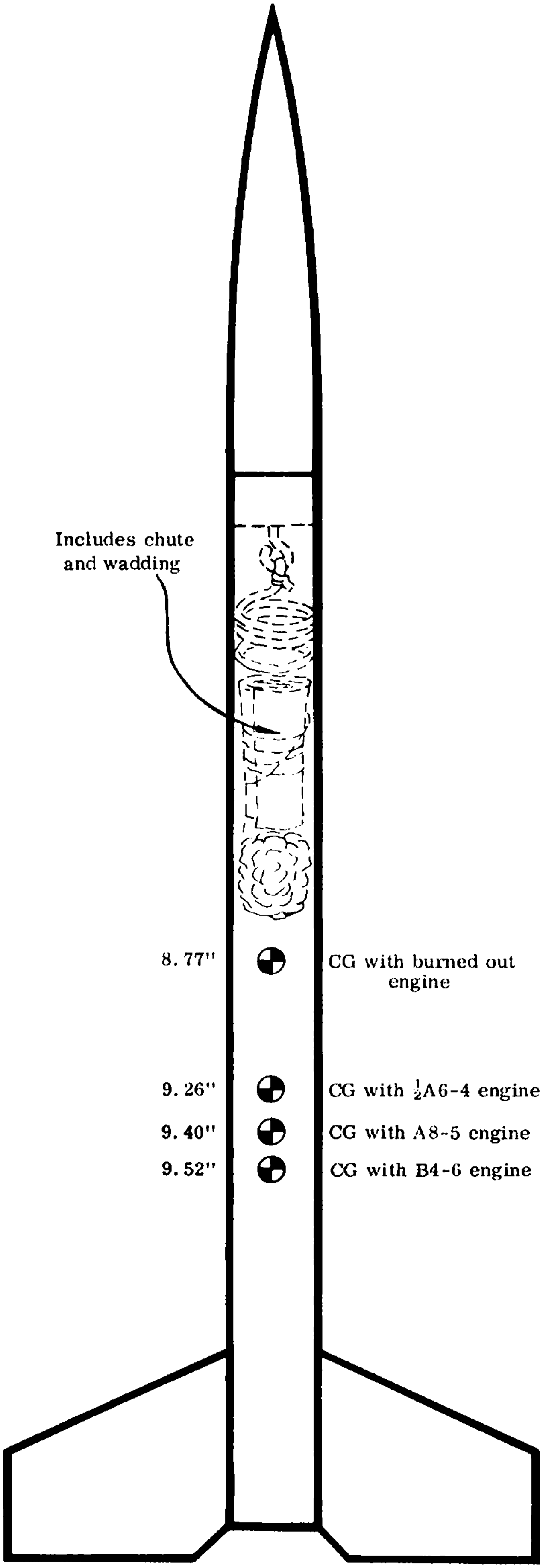
9. SAFETY

Occasionally, model rocketeers fly their new custom rocket designs without bothering to check that the static margin is adequate. They think that they have enough experience to judge whether or not a design is stable just by looking at it and are quite surprised when the first flight sometimes proves to be unstable. The rocket zig-zags and does flip-flops all over the sky immediately after leaving the launch rod and as a result the thrust is just wasted in random motion.

This approach to model rocket design is not very scientific and obviously gives no consideration to optimizing performance. Also, the time spent in repairing the damaged model after it falls back to the ground usually more than offsets the time required to do a simple stability check. A serious scale modeler would never think of risking his tremendous investment in construction time in such an unscientific manner. The proper approach with any new design is to first find the rocket's C.G. and C.P. so that stability and adequate static margin can be verified; then test fly the rocket with the lightest acceptable engine on a calm day.

You may ask "Why use the lightest acceptable engine?" Remember the propellant -- it is all at the back end and it is burning away. It is like a lump of clay on the back which is being removed a little bit at a time. If the rocket were balanced on a string, the balance point would have to be shifted forward slightly after each particle of clay was removed. The balance point on the string <u>is</u> the C.G. and the rocket will rotate only about that point during free flight. During an actual flight, the consumption (burning) of the propellant similarly causes a continuous shift in the rocket's balance point (<u>or</u> center of gravity, <u>or</u> pivot point, <u>or</u> only point where rotation occurs -- whatever makes it easiest for you to understand).

In other words, the C.G. location is not fixed. The following illustration shows the different initial balance points of a Javelin with various motors and also shows the final C.G. location after all the propellant and smoke delay is used up.



Centuri JAVELIN variations in center of gravity

Figure 42

If you never previously considered the idea of a C.G. shift during flight, you were probably intrigued to see that it actually shifts that much. Thus, one of the consequences of using a lighter engine in the first flight is that you will have a little more static margin of safety. It can also be concluded that a rocket which is stable initially will become more stable as the flight progresses because the C.G. is moving further and further ahead of the C.P.

One additional thought to consider arises occasionally from a rather special set of circumstances. Referring to the previous illustration of the Javelin -- what could be said about an initial flight with a B4-6 engine if the true C.P. location was not at the previously shown location of 11.3 inches but instead at an assumed 9.40 inches from the nose.

Initially, the C.G. is behind the C.P. and the rocket is unstable. If the rocket is going to fly unstable it will usually do so immediately upon lift-off. All the while the rocket is tumbling and flip-flopping around the sky the C.G. is shifting forward. Soon the C.P. and C.G. match at 9.40 inches -- meaning the rocket is neutrally stable. A few instants later, the C.G. is ahead of the C.P. and the rocket is in a stable condition. It is impossible to predict in just what direction the rocket will be pointing when it becomes stable and clearly, a potential hazard exists if the rocket was pointing horizontally or at a down angle.

What if this same flight was instead performed with the recommended lightest engine? Referring to the Javelin drawing again, it is noted that the rocket's C.G. with a ½A engine is ahead of the assumed C.P. to start with (9.40 inches from the nose tip). This marginal stability would not really be sufficient by our standard one body diameter stability criteria, but definitely must be considered a safer procedure than using the heavier B motor in an initial flight.

Another situation that can give rise to the unstable-to-stable flight condition is in multi-staging where the lift-off configuration is unstable, but the second stage is stable. You cannot just check the C.P. and C.G. of the second stage and conclude that the rocket will be stable. The second stage combined with its booster is an entirely different aerodynamic shape and has its own special center of pressure location. To be a stable body in free flight this C.P. must be behind the balance point of the entire two-stage vehicle.

Anyway, the only reason these rare situations can possibly occur is if the rocketeer is not conscientious and does not bother to check his C.P. and C.G. locations. Simple methods now exist to accurately check stability with confidence -- use them!

We at Centuri sincerely hope that the material presented in this report has helped to give you an appreciation and understanding of the importance of stability and along with that some motivation to use the scientific tools available at your disposal.